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THESIS

**SYNOPTIC-SCALE INFLUENCE
ON
THE MONTEREY BAY SEA-BREEZE**

by

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September 1994

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SYNOPTIC-SCALE INFLUENCE ON THE
MONTEREY BAY SEA-BREEZE

by

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Most of all, I would like to thank Martha, my wife, for her soothing understanding and undying support.

I would like to dedicate this thesis to Ryan & Alyssa, my children. I hope you both possess a thirst for knowledge as you develop through the years.

I. INTRODUCTION

The United States Navy's primary theatre of operations are now the coastal regions around the world. Since 1990 military operations have predominantly occurred in coastal environments where the effects of thermally-induced circulations, principally the sea-breeze, are a major contributor to the coastal wind patterns. Attaining a better understanding of the mesoscale influences on the coastal wind is vital to safer and more effective military operations, affecting beach assaults, missile launches, and flight operations. Understanding the dominant influences of the sea-breeze circulation, including precursor indicators and/or expected development of and maximum intensities of the sea-breeze under specified synoptic-scale pressure patterns, will enhance the United States' ability to achieve these goals.

The land/sea-breeze circulation is one of the most interesting mesoscale atmospheric phenomena observed in coastal regions during periods of fair weather. The diurnal fluctuations in the land/sea-breeze along the California coast are not completely understood with respect to variation in the synoptic-scale flow. The prevailing large-scale synoptic flow and associated vertical stability is known to directly affect the time of occurrence and the resultant intensity of the sea-breeze in other regions. The prevailing synoptic-scale

pressure pattern in California also dictates the amount of low stratus which is also known to directly affect the amount of differential surface heating that drives the sea-breeze.

This thesis investigates the relationship between the large-scale synoptic pressure patterns and the occurrence and intensity of the sea-breeze circulation around Monterey Bay, California during the summer period of May 01 through September 30, 1993. Quantitative sea-breeze characteristics are chosen to provide a general framework from which to analyze sea-breeze behavior adaptable to more general coastal locations. This study is a follow-on study to Round (1993), which described the diurnal wind intensity changes of the Monterey Bay sea-breeze. Recurrent patterns based on these sea-breeze intensity variations were used by Round (1993) to categorize the Monterey Bay sea-breeze into characteristic types. The aim of the present study is to describe the relationship between the synoptic-scale pressure pattern and the diurnal wind variation associated with the Monterey Bay sea-breeze.

Chapter II provides background that describes basic properties of thermally induced sea-breeze circulations and factors that modify their evolution. Chapter III describes the data and analysis techniques used throughout this thesis to determine characteristic synoptic-scale pressure patterns. Chapter IV examines the representative cases of strong sea-breeze occurrences in the Monterey Bay area for the

characteristic synoptic-scale pressure patterns. Chapter V presents conclusions and recommendations for further research.

II. BACKGROUND

In studying the sea-breeze, it is advantageous to first examine the general characteristics of thermally induced circulations. Then modifying influences such as the synoptic-scale flow, boundary layer depth and stability, and clouds can be described.

A. THERMALLY INDUCED CIRCULATIONS

Land and sea-breezes are the most frequently observed and studied coastal mesoscale phenomena. Land and sea-breeze circulations are produced by the **differential surface heat flux** between the ocean and the adjacent land and are restricted to coastal areas where the spatial scale of each surface is large enough to produce a significant circulation. The considerable difference in heat absorption between land and water governs the amount of surface heating which occurs and consequently the resulting difference in surface heat flux. Temperature and density gradients induce pressure gradients through the equation of state.

Thermally induced circulations demonstrate a great dependance on both **small-scale** (local) environmental conditions as well as **large-scale** (synoptic) features. The formation process begins with **insolation**, the single greatest factor which determines the forcing of thermally induced

circulations. The insolation heats the surface of the earth to varying degrees according to the albedo and heat capacity of the irradiated surfaces. **Differential heating** induces a differential surface heat flux which heats the overlying atmosphere accordingly. The air over the region with the greatest surface heat flux becomes warmer and lighter than its surroundings producing a temperature gradient between the surrounding relatively dense air. Two flows are thus started, upward motion over the region of greatest surface heat flux and horizontal motion from high pressure to low pressure.

The diurnal cycle of onshore (sea) and offshore (land) breezes is forced by the heating and subsequent cooling of the land surfaces resulting in a temperature gradient across the land-marine boundary. The land-breeze normally persists into mid-morning when radiative heating has increased temperatures over land enough to reverse the circulation induced by nocturnal radiative cooling. The **sea-breeze** increases in intensity with increased heating throughout the day reaching peak surface wind speeds by mid-afternoon corresponding to the peak in air temperature. Decreased air temperatures then permit the circulation to decay to near calm conditions during the evening prior to initiation of the land-breeze. Johnson & O'Brien (1973) indicate that a mean temperature difference of 1 deg C between land and sea is sufficient to produce a sea-breeze circulation. The magnitude of the gradient drives

the intensity of sea-breeze surface flow (Simpson, et al., 1977).

Wexler (1946) provides a range for sea-breeze onset from 0700 (local) to 1900 (local) depending on ambient conditions. Sea-breeze onset is later for stronger offshore gradient winds. Round (1993) identified the most likely time of sea-breeze onset for the Monterey Bay area to be between 0830 and 1100 PST with the most frequent time being 1000 PST.

B. LARGE-SCALE INFLUENCES

Large-scale winds over the domain of a thermally induced mesoscale circulation often dictate circulation development more than the direct forcing terms. Studies such as Estoque (1962) and Arritt (1993) have demonstrated that the direction of the ambient wind and its magnitude directly affect whether such a circulation will form and its ultimate intensity.

Arritt (1993) arrived at Four general conclusions:

i) onshore synoptic flow: The large-scale flow is in the same direction as the sea breeze and results in a weak thermal perturbation of the large-scale flow.

ii) calm to moderate opposing synoptic flow: This regime is associated with the most intense sea-breezes. The intensity of the thermally induced perturbation increases for stronger opposing flow.

iii) strong opposing synoptic flow: Vertical motions are suppressed. The horizontal velocities are weakened.

iv) very strong opposing synoptic flow: Vertical velocities and horizontal temperature gradients are weak.

The most favorable synoptic conditions for thermally induced circulations occur when the ambient wind is light in magnitude and opposite in direction to the induced circulation. The opposing flow aids in the concentration of the temperature gradient while flow in the same sense as the circulation tends to disperse or weaken the temperature gradient necessary for the thermally induced flow.

The **synoptic pressure pattern**, the influence of which is the focus of this thesis, determines the orientation of the ambient flow at any given time impacting the development of the local sea-breeze circulation. One unanimous attribute of all sea-breeze studies is that the pressure gradient, regardless of orientation, must only produce light surface winds to permit sea-breeze formation. Wexler (1946) describes the effect of surface heating on a pressure gradient oriented perpendicular to the coast while Johnson & O'Brien's (1973) study of the U.S. Pacific west coast describes the effect on the sea-breeze circulation of the synoptic pressure gradient parallel to the coast.

The prevailing surface wind vector is equally as important as the direction alone in its effect on sea-breeze intensity and time of occurrence. The sea-breeze develops as a small circulation in the vicinity of the coast in response to the

land surface heating producing a surface heat flux greater than over the water under calm to light gradient conditions.

Arritt (1993) asserts that even slight onshore flow is sufficient to suppress the thermally induced sea-breeze and that offshore flow up to 11 m/s permits sea-breeze formation. The strongest sea-breeze circulation develops with light offshore winds owing to the location of the sea-breeze surface convergence zone below an area of neutrally stable or unstable air. The **strong stability** associated with a subsidence inversion over water causes a weaker sea-breeze when offshore winds keep the sea breeze convergence zone from reaching the shore. This results in the sea-breeze circulation existing offshore, remaining undetected at inland surface reporting stations. Very strong offshore prevailing winds prevent the necessary development of the pressure and temperature gradients which ultimately induce the sea-breeze circulation.

C. BOUNDARY LAYER DEPTH INFLUENCES

The **subsidence inversion** associated with a high pressure system over the coastal region, specifically the Pacific Northwest, restricts upward motion which lowers the **boundary layer depth** and may effectively limit the depth of onshore flow of the sea-breeze circulation (Skupniewicz, et al., 1991). According to Wexler (1946) an increase in depth of the onshore flow results in an increase in surface wind velocity and relative humidity and accompanying decrease in

temperature. Johnson & O'Brien (1973) reported that the onshore flow takes place almost entirely below the base of the inversion (within the marine boundary layer). A distinct wind speed maximum follows the sea-breeze front inland. At the coast, the marine layer appears to deepen at the onset of the sea-breeze. They also indicated that the depth of the marine inversion increases in height with the onset of the sea-breeze. This stable stratification may decrease the intensity and ultimate depth of landward penetration of the circulation (Estoque, 1962).

Along the eastern portion of the East Pacific Anticyclone, the immediate inland areas receive intense daytime heating which produces a **large-scale northerly** gradient wind flow along the coast. This persistent northerly component in the surface wind accounts for the occurrence of the coastal oceanic upwelling phenomenon which acts to lower the nearshore sea surface temperature. This combination of intense inland heating and the cold sea surface temperature produces very high **coastal thermal gradients** which lead to the development of strong sea-breeze circulations.

D. CLOUD INFLUENCES

Clouds **reflect** and **absorb insolation** reducing the amount of shortwave radiation available for surface heating. Thus clouds play a role on the extent and intensity of the sea-breeze circulation. They prevent sufficient heating of the

land surface restricting the development of a strong enough thermal gradient necessary for a sea-breeze flow. With clear skies, the direct correlation between the increasing sensible heat flux and air temperature through the day is paramount to the occurrence of the induced thermal circulation. It is important to note that the maximum heat flux occurs at midday while the air temperature response is delayed several hours.

Various studies [Wexler (1946), Fisher (1960), Simpson (1964)] identify local weather conditions favorable for the production of a sea-breeze circulation. The two most dominant conditions are clear skies and light winds. These two factors allow sufficient surface heating preventing the sea-breeze from being overwhelmed by the ambient flow. Wexler (1946) identified a percentage of existence of the sea-breeze circulation during various cloud conditions:

Scattered clouds (0-5 tenths) = 90 %

Broken clouds (6-9 tenths) = 39 %

Overcast clouds (10 tenths) = 27 %

The **prevailing synoptic** weather pattern over California directly influences the sea-breeze development and intensity by dictating the direction and intensity of the prevailing wind. Cloud presence and onshore/offshore cloud advection affect sea-breeze circulation as indicated by Round (1993). Clouds over the coastal region prevent sufficient heating of the land surface to build a strong thermal gradient thus preventing sea-breeze flow.

E. MONTEREY BAY SEA-BREEZE CATEGORIES

There are four identifiable categories base on Round's (1993) sea-breeze categorizations:

1. Gradual development

Consistent with Wexler's identifications, the gradual development type of sea-breeze forms with either the pressure gradient oriented parallel to the coast with resultant alongshore winds or with the pressure gradient perpendicular to the coast and light, onshore winds. Thus the prevailing winds have a significant effect on the sea-breeze formation. The sea-breeze forms as a small circulation in the immediate vicinity of the coast (Hsu, 1970). This gradual type displays a more subtle onset of onshore flow. It is also a classical thermally driven mesoscale circulation between land and sea. After formation the circulation spreads both landward and seaward, increasing in vertical extent. Upward motion and onshore flow result from the heating of the air directly over the land surface (Wexler, 1946). This gradual development type of sea-breeze circulation includes all days in which a definite sea-breeze occurred without a clear and definite time of onset.

2. Clear onset

This type of sea-breeze circulation is very similar to the gradual development type differing only in the onset signal. This type includes all days in which either a

definite wind shift without a speed increase occurred or onshore wind conditions prevail prior to sea-breeze onset with onset identified by a distinct increase in onshore wind speed.

3. Frontal

The frontal type of sea-breeze circulation develops when the pressure gradient is oriented perpendicular to the coast with offshore winds and is distinguishable by definite frontal characteristics. This frontal type displays a more abrupt change in wind and temperature difference. It is produced by a combination of offshore advection effects and thermal contrast. Offshore advection piles up relatively cold air over water producing an offsetting pressure gradient which balances the ambient wind. The resulting instability from continued heating over land allows the pressure gradient over water to overcome the prevailing winds. Once the circulation is established, thermal contrast reinforces the sea-breeze. This frontal type forms over water. Once equilibrium between the ambient flow and high pressure over water is destroyed, the frontal sea-breeze advances inland. Flow is initiated in the cold airmass from the induced vertical motion between offshore advection overriding the cold marine airmass and is sustained by the thermally induced pressure gradient and associated rising motion toward the inland convergence zone. Downward motion over the water is a consequence of continuity

resulting from horizontal divergence caused by the evacuation of cold air toward land.

4. Double surge

This sea-breeze circulation category includes all days in which two separate and distinct onshore events occurred.

F. PACIFIC WEST COAST

The dominant synoptic-scale feature, characteristic of this region, is the **North Pacific high** pressure system during the spring and summer months which dominates the ocean and adjacent coastal regions. This semi-permanent synoptic-scale feature is responsible for the frequent coastal fog and **low-level stratus** occurrences associated with large-scale subsidence inversions over relatively cold ocean surface water. This semi-permanent high also determines the direction of the large-scale ambient wind which is generally either onshore or parallel to the coast producing coastal northerlies.

The consequence of this semi-permanent synoptic feature indicates that the gradual development type sea-breeze circulation is expected throughout the summer months along the Pacific West coast (Round, 1993). The frequent low-level stratus routinely plays a role in the development of the sea-breeze.

The topographical effects of the California coast cause a significant large-scale diurnal temperature difference between

the central valley bounded by the coastal and Sierra Nevada mountain ranges and the cold ocean surface water produced by coastal upwelling. This interaction forms a large-scale continent-ocean wind circulation system larger in scale than the sea-breeze circulation. This larger-scale thermally induced continent-ocean circulation makes it difficult at times to distinguish between it and the sea-breeze circulation. The concavity of the Monterey Bay should diminish the inland convergence of the sea-breeze circulation if the circulation is oriented perpendicular to the central coastline of the bay. A southerly orientation down the Salinas valley may reduce this effect (Round, 1993).

Results from CODE (Coastal Ocean Dynamics Experiment) concerning the summer surface wind and current data along the U.S. Pacific west coast of 1981 & 1982 demonstrate the intense effect of subsidence due to the Pacific anticyclone. This Pacific high is responsible for the predominantly alongshore surface winds during the spring/summer months. The local heating of the land surface creates the sea-breeze effect to directly trigger the lowering of the marine inversion along the coast which lowers the height (approximately 300 m above sea level) of the diurnally fluctuating, intense lower atmospheric **alongshore jet** (Beardsley, et al., 1987). The results of the CODE study indicate one of the best descriptors of the sea-breeze flow along the California coast is the

clockwise turning of an initially cross-coastal surface wind flow.

III. SEA BREEZE DATA ANALYSIS

A. CHARACTERISTIC SYNOPTIC-SCALE PATTERNS

Twelve hourly NMC Global Data Assimilation System (**GDAS**) final analysis data and locally generated three hourly surface analyses from May 01 to September 30, 1993 were examined in an effort to characterize the dominant synoptic-scale pressure patterns prevailing over the Eastern Pacific/Western U.S. region and to determine the influence each had on the sea-breeze in the Monterey Bay area (Fig 1) during the period. This summer period encompassed 153 days and 1224 pressure analyses. Each three hourly analysis during this period was examined to ascertain the dominant synoptic-scale pressure patterns over California. Three such patterns were identified as dominant throughout the period of study. These three characteristic patterns will be referred tc as the **Ridge**, **Trough**, and **Gradient regimes**. The average sea-level pressure distribution was calculated for each synoptic-scale pattern by simply summing the observed pressures at each grid point in the 00Z & 12Z GDAS analysis for a given pattern and then dividing the total by the number of analyses. Throughout this study, **00Z corresponds to 1700 PST** while **12Z corresponds to 0500 PST**. The mean pressure distribution for the Ridge, Trough, and Gradient regimes are shown in Figs 2, 3, and 4

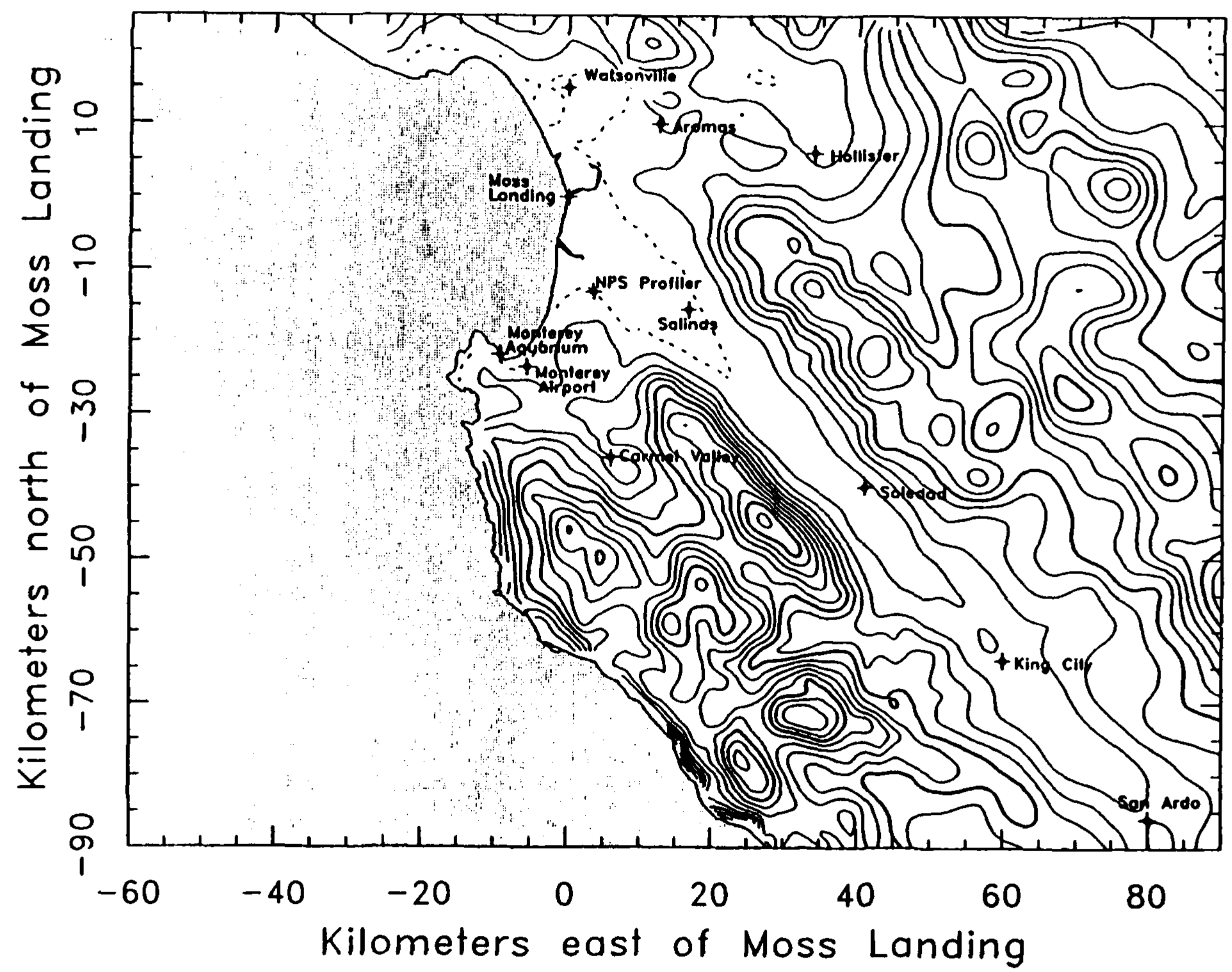


Figure 1. Topographical map of the Monterey Bay coastline and Salinas Valley.

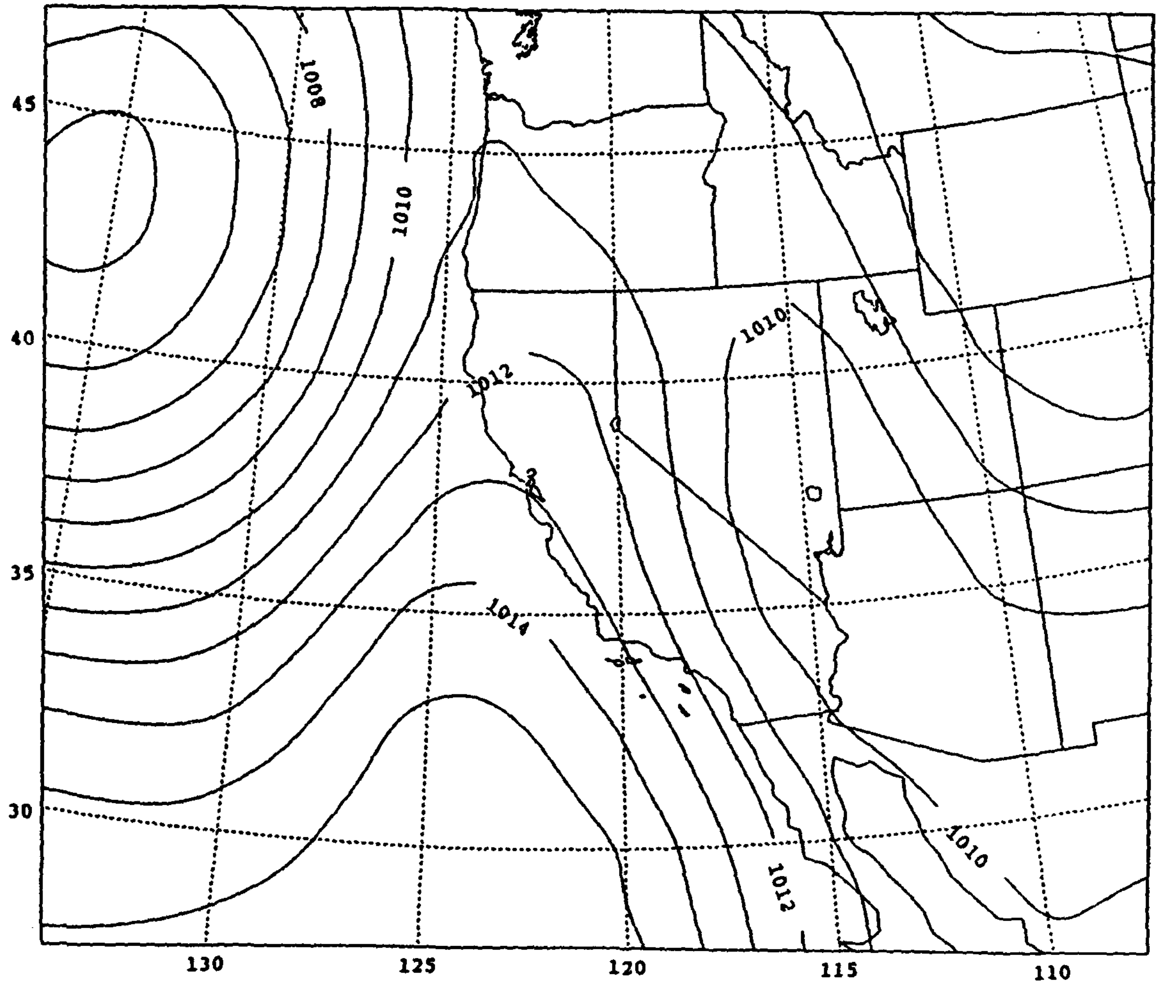


Figure 2. Mean Ridge regime pressure distribution for May - Sep 1993.

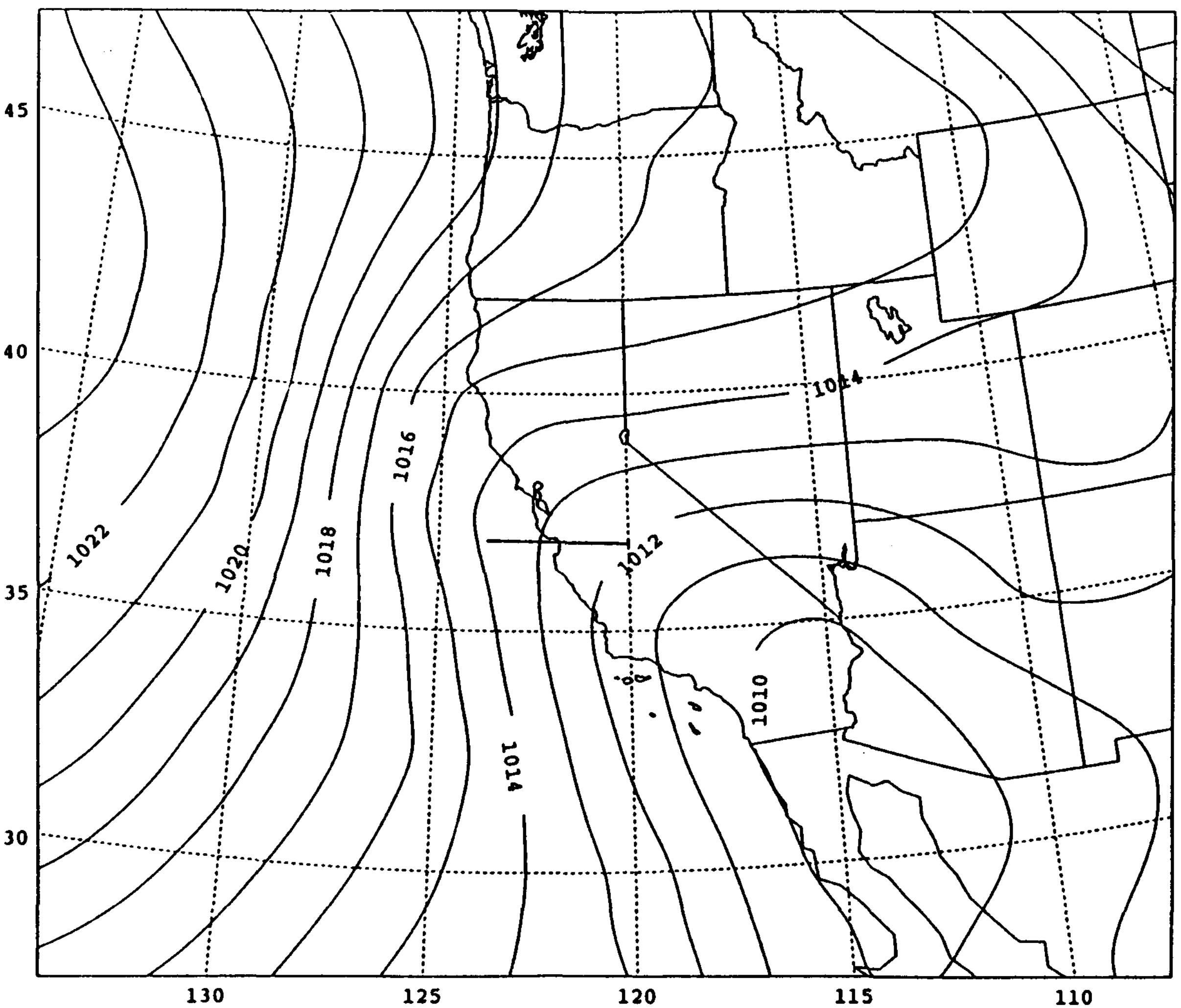


Figure 3. Mean Trough regime pressure distribution for May - Sep 1993.

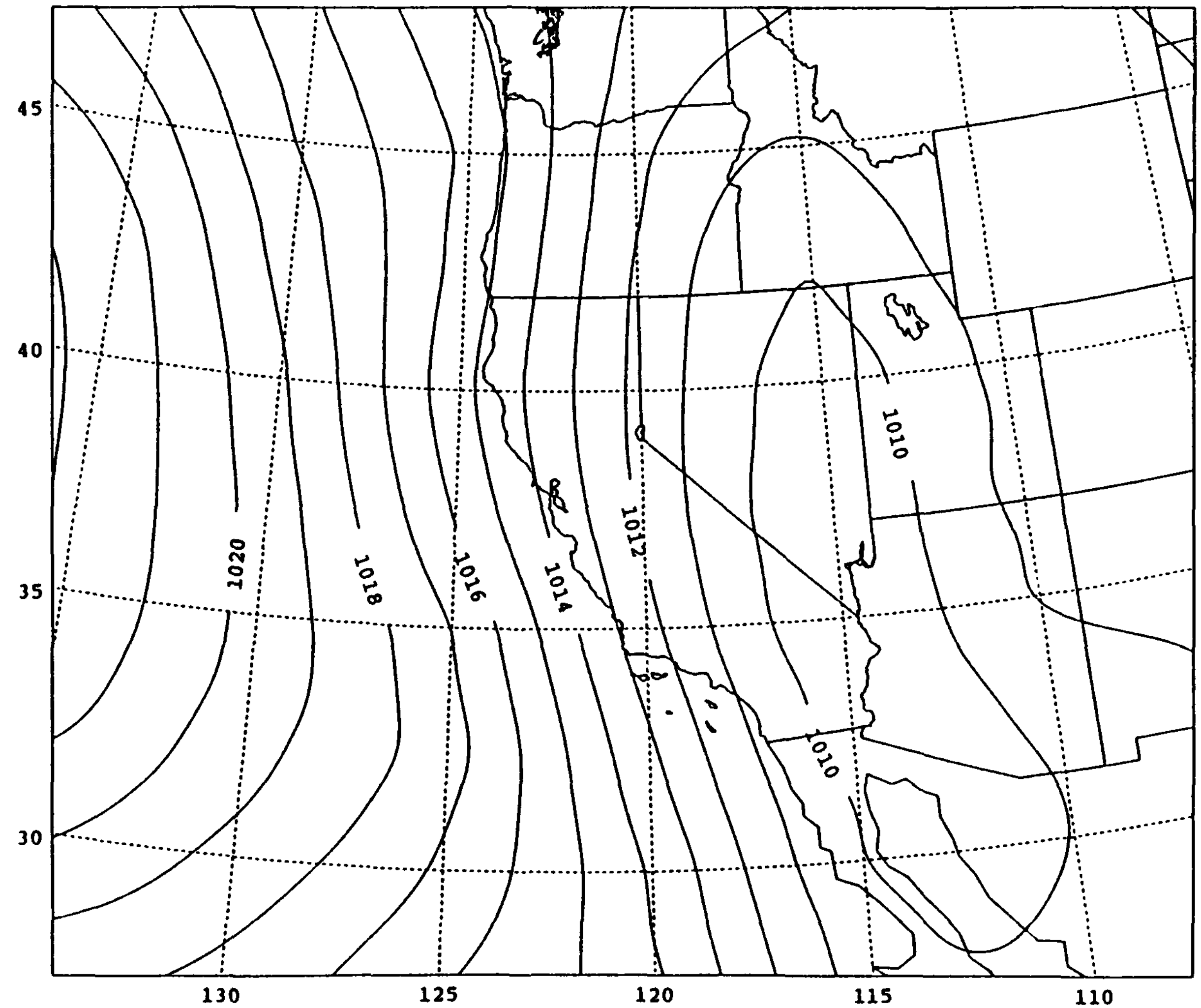


Figure 4. Mean Gradient regime pressure distribution for May - Sep 1993.

respectively. Separate means for the 00Z & 12Z analysis times were also calculated to identify any characteristic diurnal variation in these basic pressure patterns.

The sea-level pressure pattern for the Ridge regime, 36 total twelve hourly analyses, is characterized by a ridge axis that extends north to south along the west coast (Fig 2). Offshore, a low pressure center occurs along 135W between 40N and 45N. In addition, the Great Basin region has relatively low pressure. The 00Z and 12Z mean pressure patterns, 18 twelve hourly analyses each, indicate that the ridge axis shifts in an identifiable diurnal cycle. The 00Z mean ridge axis is located offshore (Fig 5) while the 12Z mean ridge axis extends in a southwest to northeast orientation across coastal California into northwest Nevada (Fig 6). This east-west shift in the ridge axis position is consistent with nighttime pressure increases and daytime pressure falls over the interior regions of California, Oregon, Washington, and Nevada. The offshore low pressure center during this regime typically remained quasi-stationary for 24-48 hours before moving north to merge with the parent low pressure center in the Gulf of Alaska.

The sea-level pressure pattern for the Trough regime, 148 twelve hourly analyses, is characterized by an inverted low pressure trough extending from southeast to northwest through central California (Fig 3). Offshore, the Eastern Pacific semi-permanent high pressure system is centered north of 40N

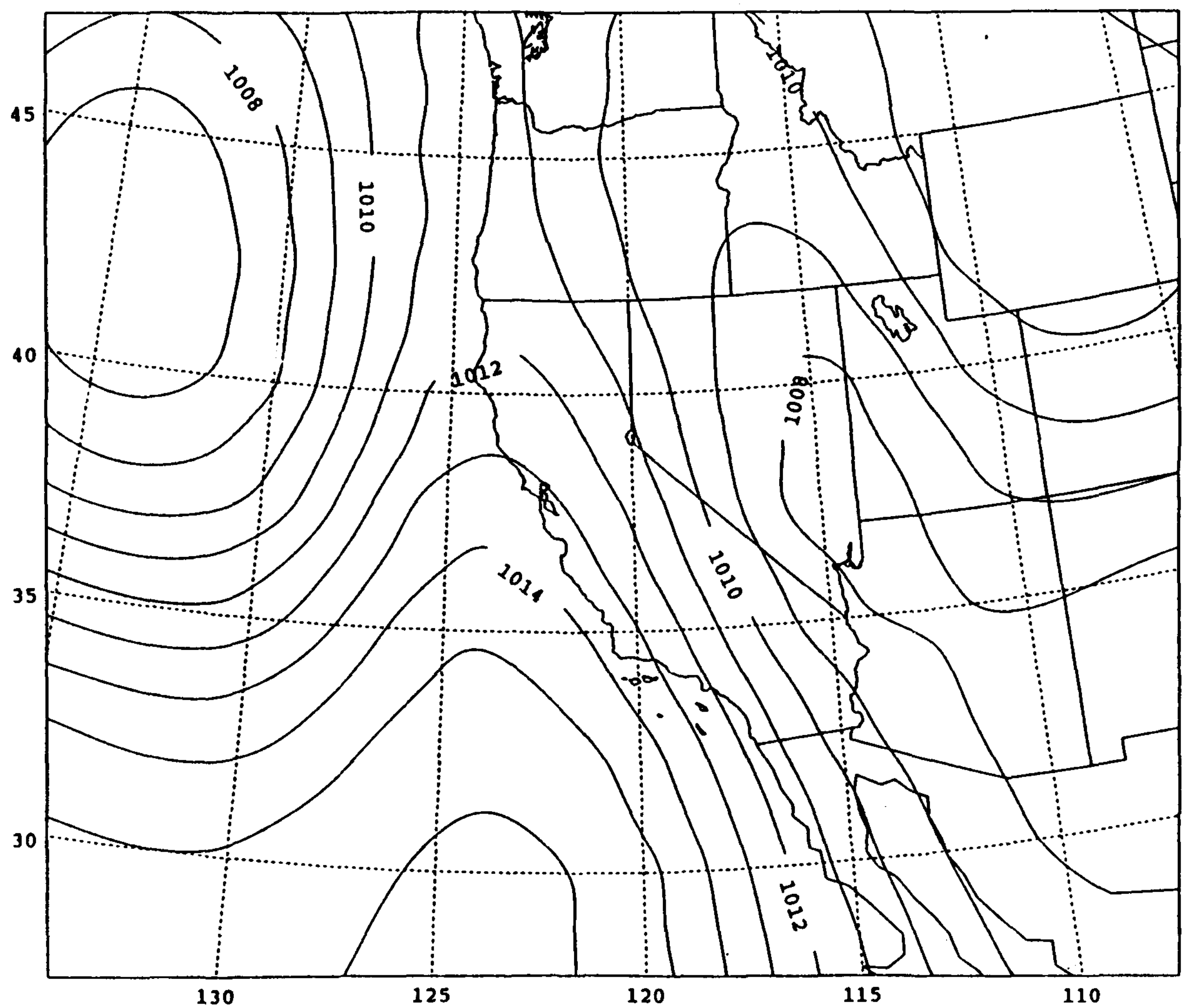


Figure 5. Same as 2 for 00Z only.

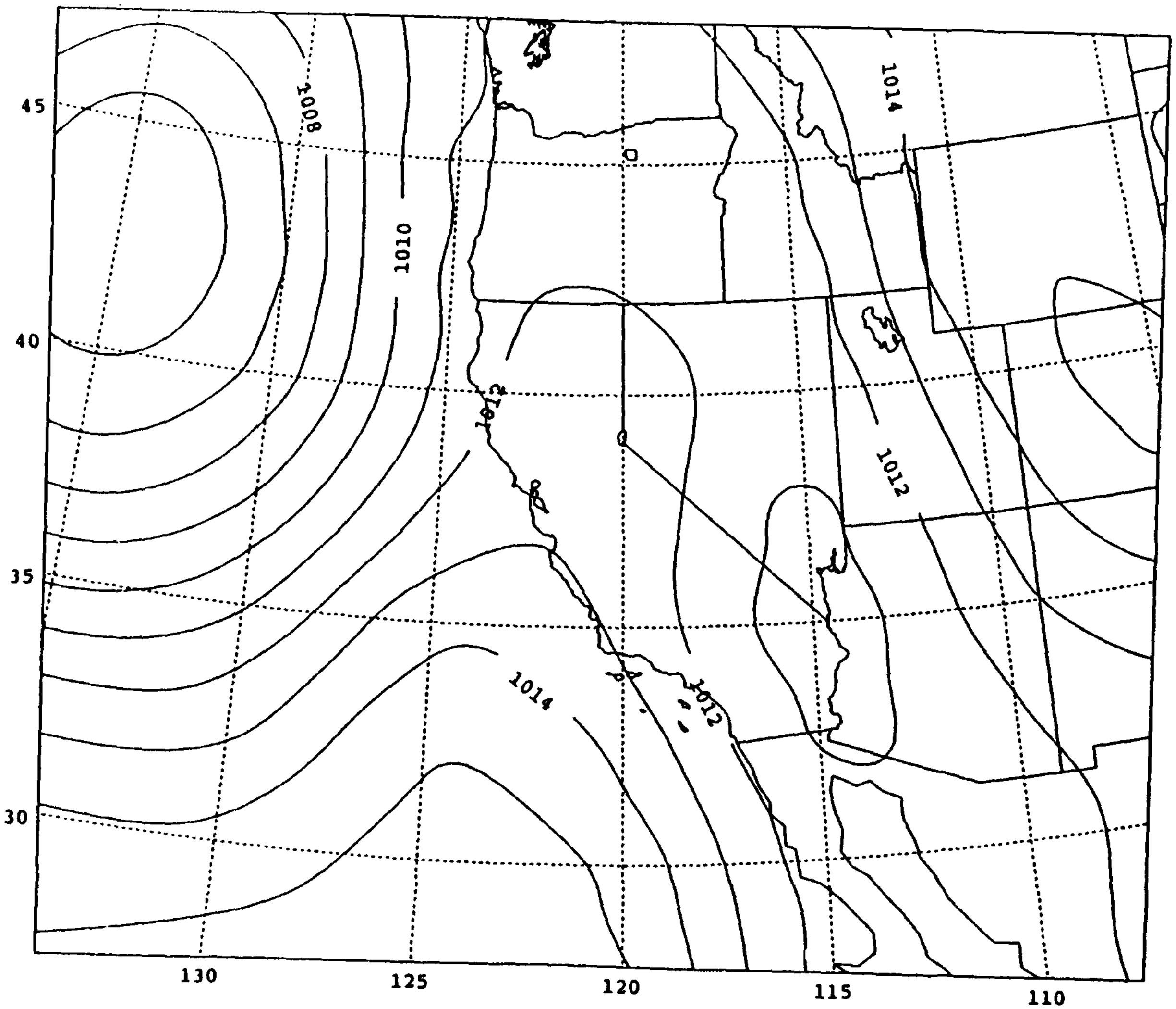


Figure 6. Same as 2 for 12Z only.

and west of 135W with a prominent ridge axis extending eastward into Colorado. This mean trough pressure pattern was also further divided into a 00Z and 12Z mean pressure pattern, 69 & 79 twelve hourly analyses respectively, indicating that the trough axis also shifts in an identifiable diurnal cycle. The 00Z trough mean reflects a trough axis extending from southwest Arizona northwestward to the northwest California coast (Fig 7). The 12Z trough axis was similar to the overall trough mean, except the trough axis extended offshore south of Monterey Bay (Fig 8). This east-west shift in the trough axis position is consistent with nighttime pressure increases and daytime pressure decreases over the interior regions of California, Oregon, Washington, and Nevada, similar to the diurnal shift in the ridge axis position mentioned previously. The quasi-stationary Eastern Pacific high typically is centered along 135W between 35N & 40N during this regime with a prominent ridge axis extending eastward into Washington and Idaho. Through the 24 hour period of a strong sea-breeze day, the onshore ridge builds southeastward into central Nevada.

The sea-level pressure pattern for the Gradient regime, 78 twelve hourly analyses, is characterized by an inverted low pressure trough axis extending north from southeast Nevada to northwest Idaho (Fig 4). The Eastern Pacific semi-permanent high pressure system was centered west of 135W during this regime dominating the entire Eastern Pacific ocean. The resultant pressure gradient between these two synoptic-scale

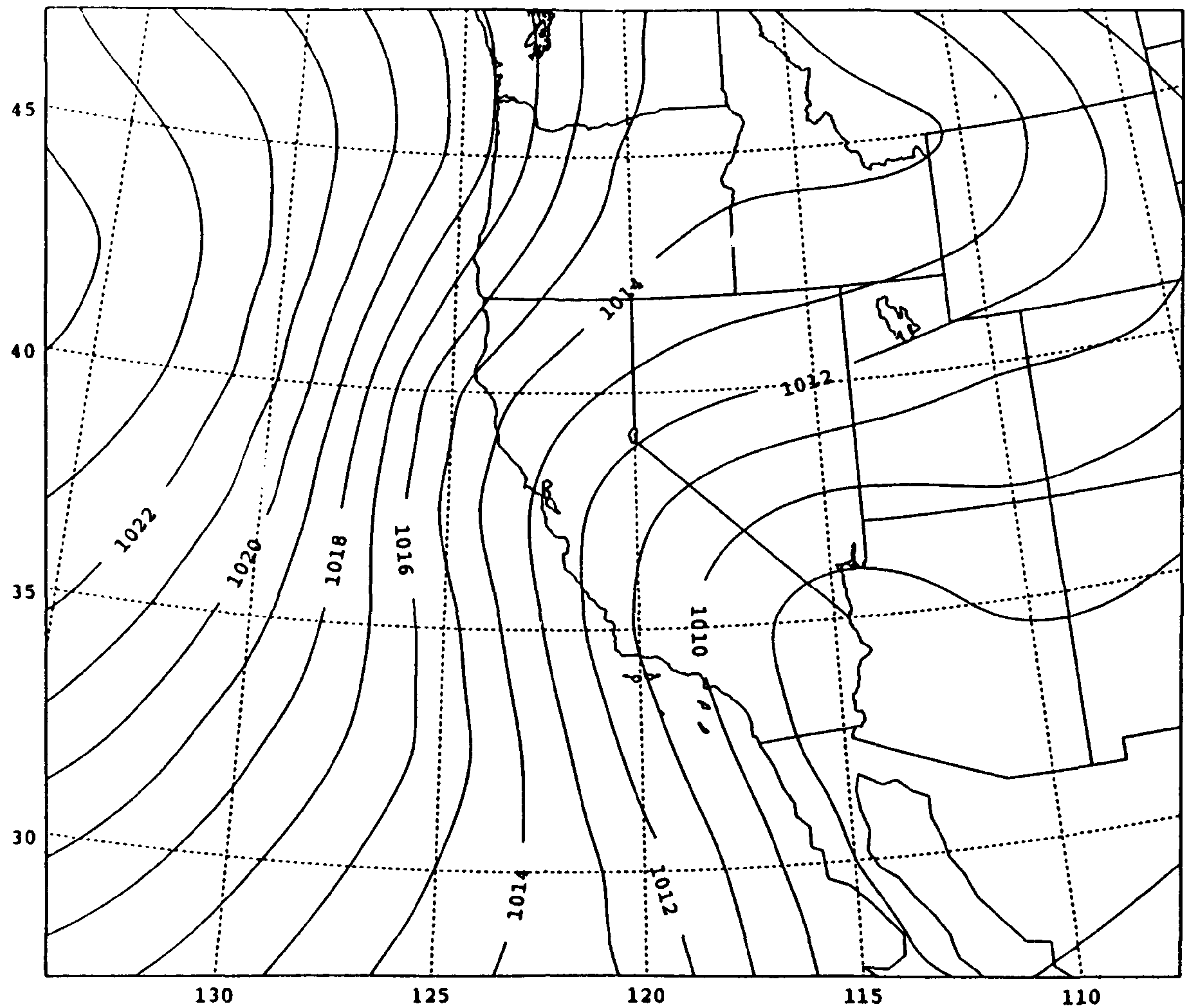


Figure 7. Same as 3 for 00Z only.

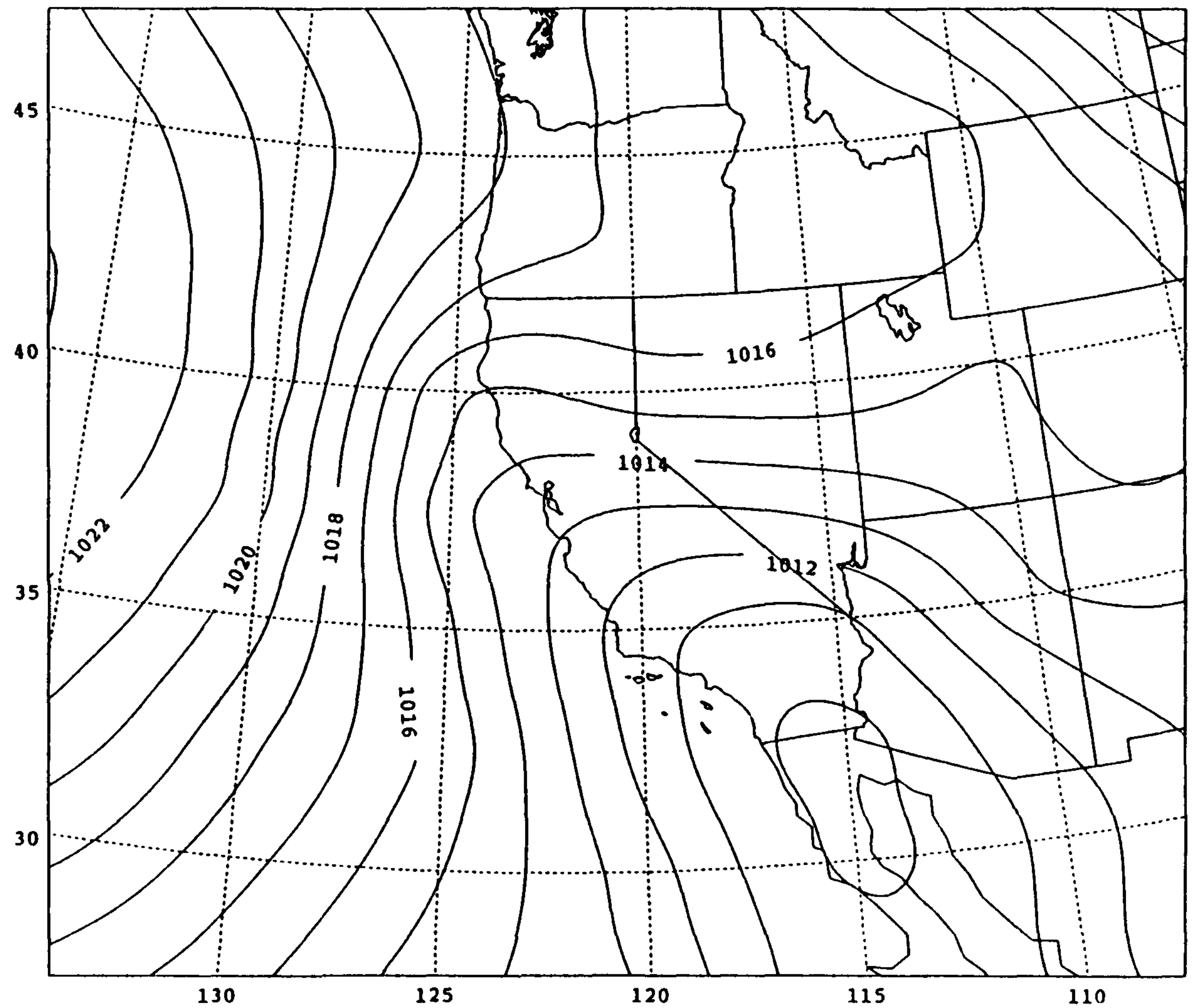


Figure 8. Same as 3 for 12Z only.

systems prevailed over the entire coastal California region. The resultant orientation of the thermal trough axis dictates the relative tightness of the surface pressure gradient, as depicted in Fig 3, by the **small dark horizontal line** measuring the pressure gradient over Monterey Bay. The 00Z and the 12Z mean pressure patterns, 46 & 29 twelve hourly analyses respectively, indicate that the Gradient regime is more representative of a transitional flow pattern responding to the eastward or westward migration of the western U.S. thermal trough axis. The 00Z mean surface pressure pattern (Fig 9) indicates a 3.3 mb surface pressure gradient exists over the Monterey Bay as compared to a 2 mb surface pressure gradient for the 12Z mean surface pressure pattern (Fig 10). This intensification and relaxation of the pressure gradient is again consistent with the diurnal pressure changes associated with strong daytime heating inland.

B. SELECTION OF CASE STUDIES

Ten case studies were selected for a more complete analysis of the interaction of the synoptic-scale pressure patterns with the sea-breeze in Monterey Bay. The specific sea-breeze cases were chosen based upon the ambient wind equalling or exceeding 10 kts under different characteristic synoptic-scale pressure patterns. This resulted in two ridge cases, four trough cases, and four gradient cases as listed in Table 1.

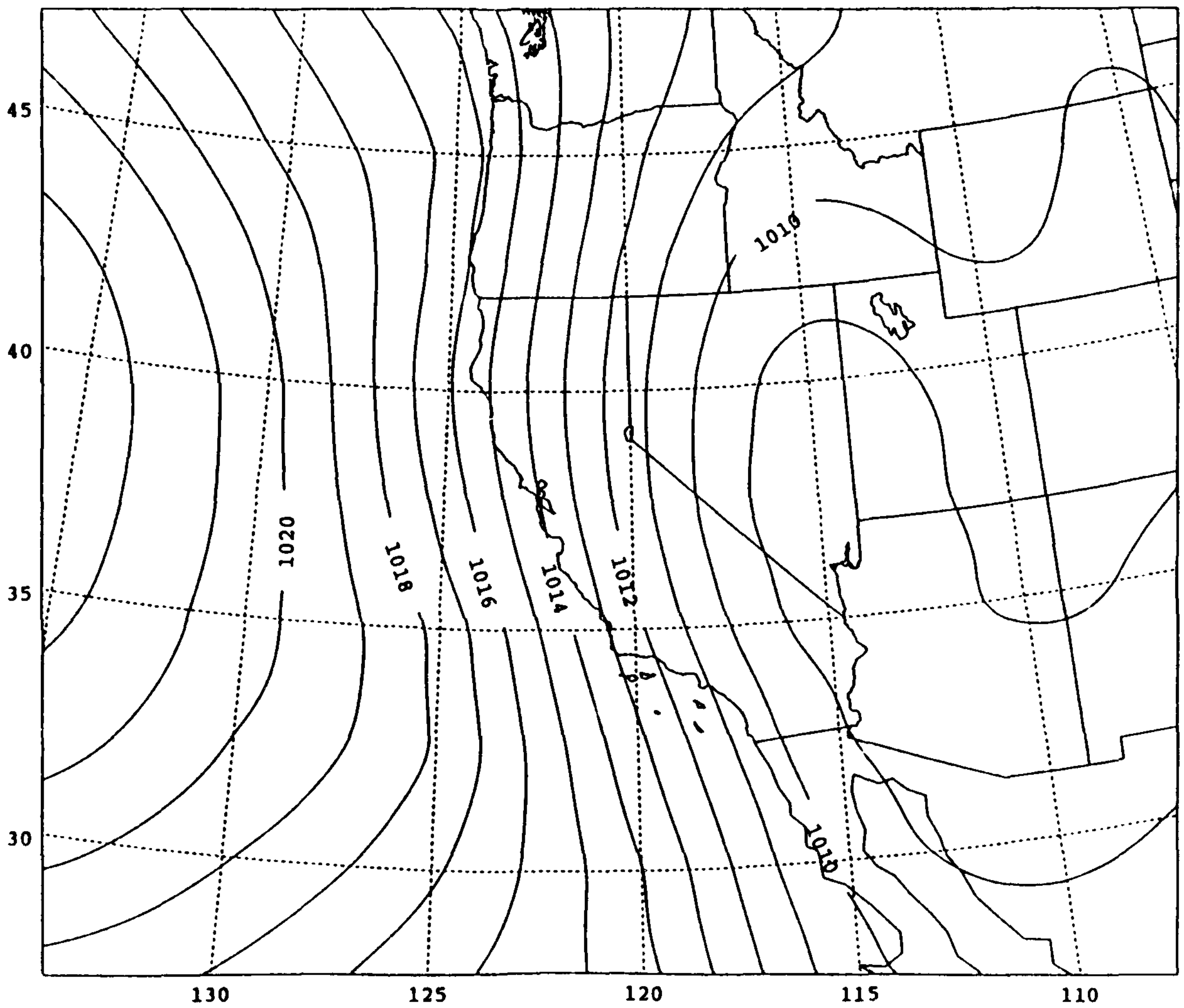


Figure 9. Same as 4 for 00Z only.

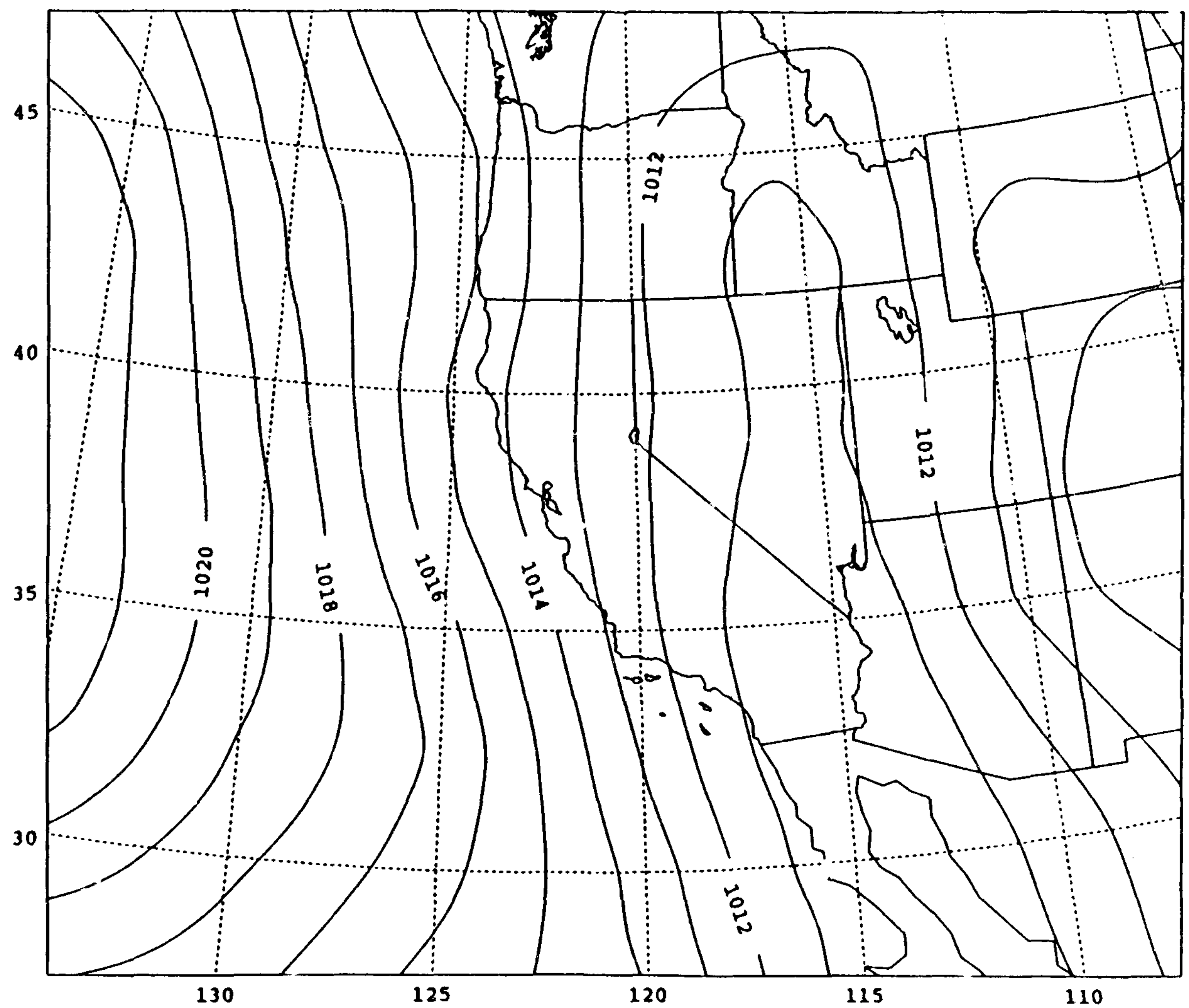


Figure 10. Same as 4 for 12Z only.

Case #	24 HR Sea-Breeze Period	Synoptic Scale Regime
1	May 14/06Z - 15/06Z	Ridge
2	May 25/06Z - 26/06Z	Ridge
3	June 08/06Z - 09/06Z	Trough
4	June 11/06Z - 12/06Z	Gradient
5	June 17/06Z - 18/06Z	Trough
6	June 19/06Z - 20/06Z	Trough
7	June 21/06Z - 22/06Z	Gradient
8	July 02/06Z - 03/06Z	Gradient
9	July 13/06Z - 14/06Z	Gradient
10	Sep 20/06Z - 21/06Z	Trough

Table 1. 10 Selected case studies.

Upon selection of the cases, the sea-level pressure analyses were regenerated every three hours for the 24 hour period from 06Z to 06Z (2300 PST) enveloping the strong wind day. The available ship, buoy, and land station observations and the NMC analyses, interpolated to the analysis time, were blended using the multiquadric analysis technique (Nuss & Titley, 1994). The NMC analyses served as a first guess to fill in holes in the observations, where no observations occurred within 300 km of the previous observation. These locally produced surface pressure analyses for the Eastern Pacific and Western U.S. region were then used to define various sea-breeze parameters.

C. CHARACTERISTIC MONTEREY BAY SEA-BREEZE

Data used in sea-breeze analysis consisted of a time series of hourly station reports recording wind speed, wind direction, visibility, and cloud cover from the Monterey airport (Fig 1) constructed utilizing **GEMPAK** (General Meteorological Package) for each of the ten case studies. The result is a series of analyses covering 153 days summarized by 10 select cases consisting of 24 hours each revealing surface ambient wind speed intensity fluctuations for the Monterey Bay area.

As determined from the 10 cases of strong sea-breeze occurrences, the sea-breeze for the month of May in Monterey Bay is typically northwesterly with a peak wind speed of 15

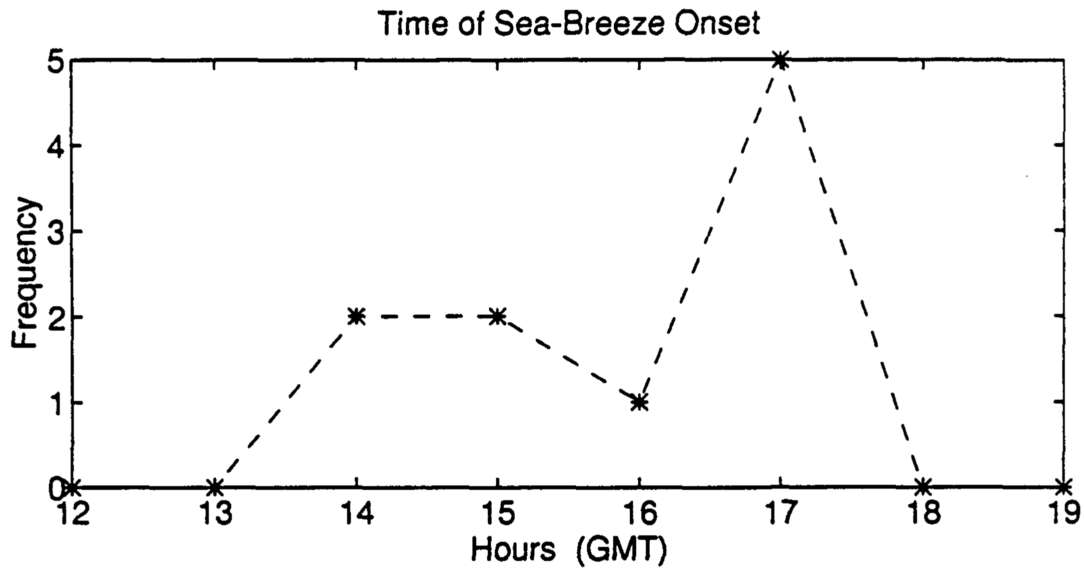
kts as depicted by the time series during cases 1 & 2 between 21Z (1400 PST) & 01Z (1800 PST). The sea-breeze for the month of June is typically west-northwesterly with a peak wind speed of 15 kts at 00Z. The sea-breeze for the month of July is typically west-southwesterly with a maximum wind speed of 18 kts at 21Z & 00Z. The sea-breeze for the month of September is typically westerly with a maximum wind speed of 12 kts at 21Z.

The sea-breeze time of onset and time of wind speed maximum for the ten cases investigated is best described by Fig 11. One half of the ten cases studied had the sea-breeze time of onset at 17Z (1000 PST) while 40% of the cases had the time of peak sea-breeze intensity at 00Z (1700 PST).

These findings are consistent with Round (1993), which used the **Fort Ord** meteorological station (NPS profiler depicted in Fig 1) maintained by the Naval Postgraduate School, with the following exceptions:

1) Round (1993) found the months of maximum sea-breeze intensity to be April, May, & June for the Monterey Bay area. This thesis finds Monterey Bay's maximum wind speed associated with the sea-breeze to gradually increase from May (12-15 kts) to July (17-18 kts), then taper off through September (10-12 kts).

2) Round (1993) found that the time of sea-breeze onset for Monterey Bay to be between 0830 & 1100 PST with the most frequent time of onset being 1000 PST. This study finds



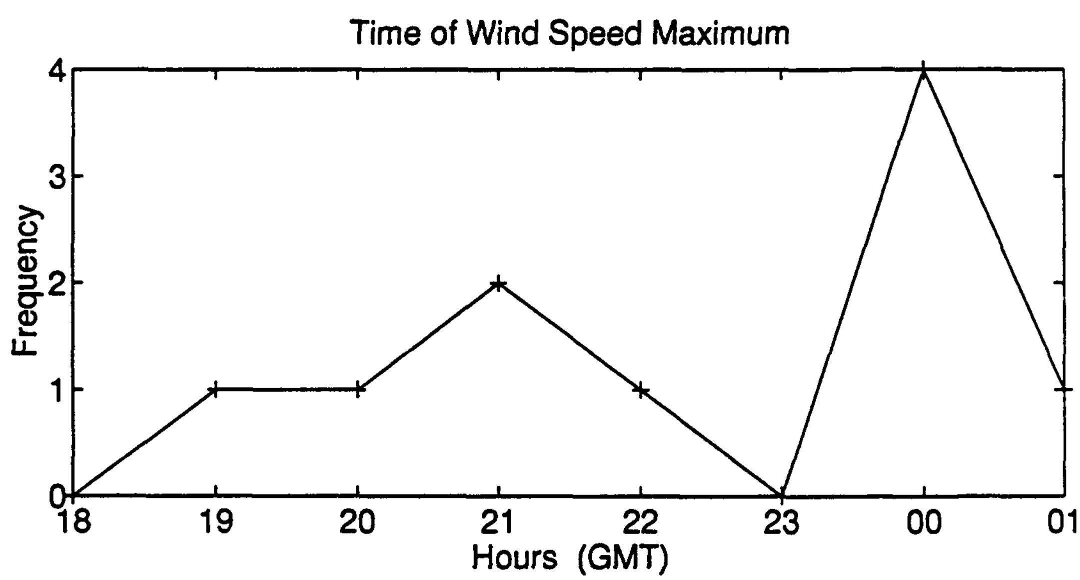


Figure 11. Time of Sea-Breeze onset & wind speed maximum.

the time of sea-breeze onset at the Monterey Bay airport to be slightly earlier, 0700-1000 PST, with the most frequent time of onset being similar to Round (1993) at 1000 PST. Onsets later than 1000 PST were non-existent for the ten select strong sea-breeze days (Table 2).

D. CHARACTERIZATION OF FACTORS INFLUENCING THE SEA-BREEZE

As the cross-coast pressure gradient primarily drives the sea-breeze, a simple technique was utilized to determine the surface pressure gradient over the Monterey Bay at each three hour time interval. The intent here was to invoke a simple and uniform means of determining the surface pressure gradient over the Monterey Bay and to evaluate its correlation to the diurnal surface wind speed fluctuations. Additionally, this technique can be used as a quick analysis tool by any on-scene forecaster/analysist. A straight edge was applied in a cross coast angle, 3/8 " on either side of the eastern boundary of Monterey Bay, which corresponds to a distance of 275 km. This was consistently applied to each analysis so that the relative surface pressure gradient in mb was determined (Fig 3). Surface ambient wind speed intensity and direction were extracted from the time series computed for each case for comparison to the corresponding pressure gradient.

As atmospheric stability is believed to be a major factor in diurnal ambient wind speed fluctuations, twice daily rawinsonde soundings taken at Oakland, California airport

Case #	06Z	09Z	12Z	15Z	18Z	21Z	00Z	03Z	06Z	Time Onset
1	Calm	Calm	12005	10005	32005	32012	32012	24006	24005	16Z
2	20005	Calm	Calm	Calm	27008	32015	16010	14007	10005	17Z
3	32005	Calm	Calm	27005	29010	32015	27012	27010	24005	15Z
4	26008	26008	26007	30010	34010	34010	27015	24007	22006	14Z
5	Calm	12003	12006	12006	32005	33006	32007	35007	Calm	17Z
6	Calm	Calm	Calm	Calm	34005	27010	27014	Calm	Calm	17Z
7	24007	24006	24005	30010	30008	32012	29015	24006	24005	15Z
8	Calm	Calm	Calm	24005	27005	27018	27018	29005	Calm	14Z
9	Calm	Calm	Calm	Calm	22012	24014	27010	24006	Calm	17Z
10	Calm	Calm	Calm	Calm	27006	26012	26010	Calm	Calm	17Z
	06Z	09Z	12Z	15Z	18Z	21Z	00Z	03Z	06Z	

Table 2. Summary of 10 case studies. Wind is listed as direction/speed (dirsp).

(00Z/12Z) were analyzed and the depth and stability of the marine boundary layer were correlated to the diurnal variability of the Monterey Bay sea-breeze.

Oakland airport rawindsonde soundings (OAK) were chosen to best represent the Monterey Bay area's vertical atmospheric structure in the absence of routine rawindsonde soundings taken in the immediate Monterey Bay area. Simultaneous with this thesis study during the spring/summer of 1994 was the Monterey Area Ship Track (**MAST**) experiment hosted by the Naval Postgraduate School. Daily rawindsonde soundings were taken at the Naval Postgraduate School (30m height) which is located approximately 200m inland from the Monterey Bay coastline. The soundings taken at the Naval Postgraduate School were compared for the month of June 1994 with the corresponding soundings taken at the Oakland airport. The results (Figs 12 & 13) indicate a strikingly **similar** inversion height between Oakland, California and Monterey, California despite the 220 km separating the two cities. This result supports the use of the Oakland soundings to represent the Monterey Bay vertical atmospheric structure in the absence of local atmospheric soundings.

The influence of stratus on the Monterey Bay sea breeze was determined from the analysis of the Monterey (MRY) airport station reports. Utilizing a time series of MRY station reports, the change in amount of stratus and the corresponding change in ambient wind speed was easily identifiable. One

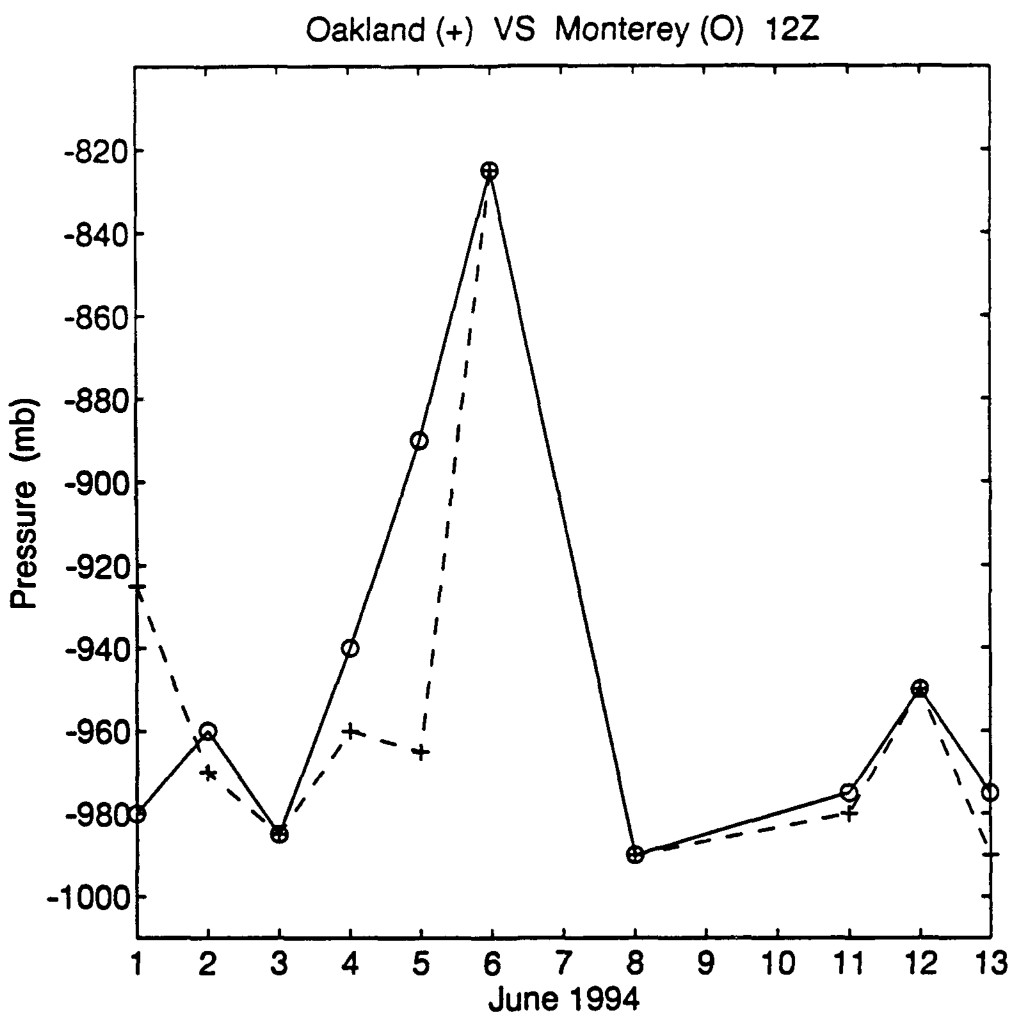


Figure 12. Oakland California-vs-Monterey California atmospheric sounding comparison for 1-13 June 1993.

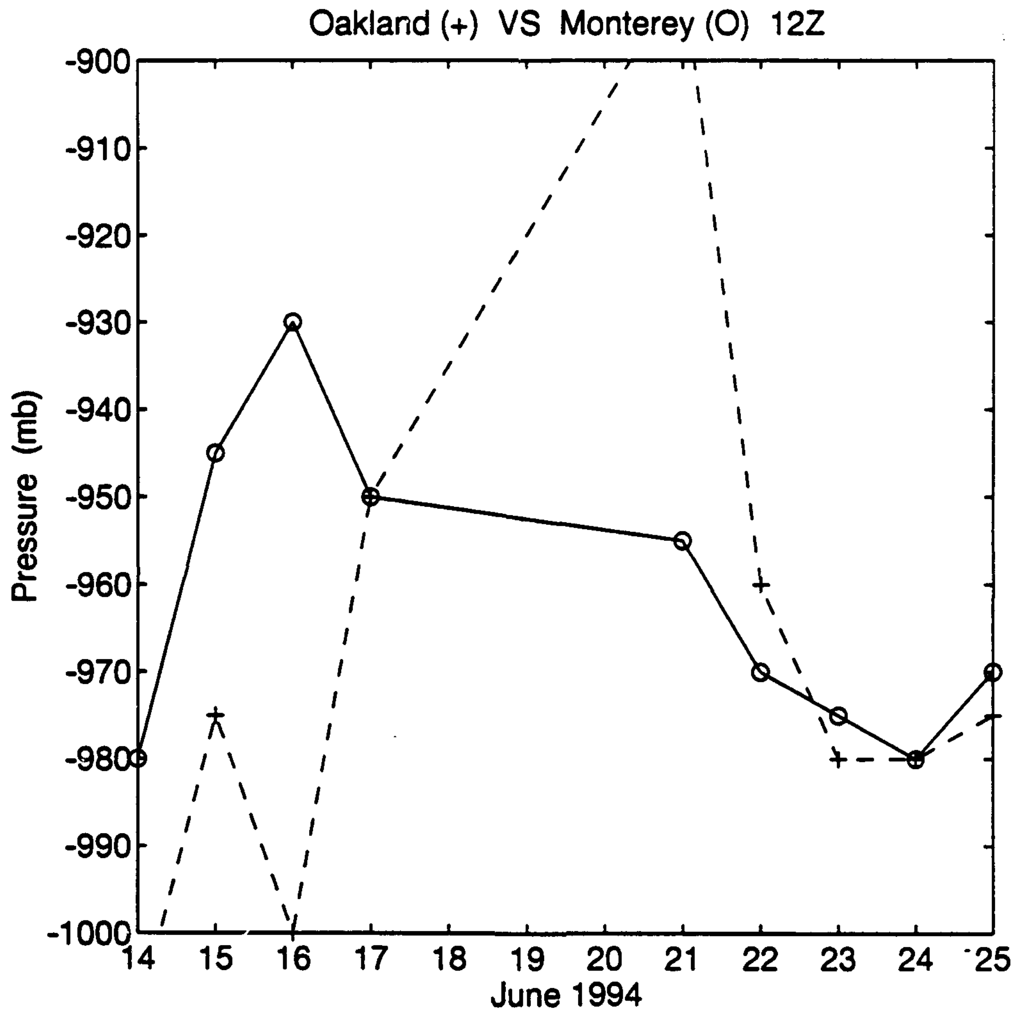


Figure 13. Same as 12 for 14-25 June 1993.

drawback to using MRY station reports was that the airport stopped reporting during the 2300 and 0500 (PST) time period. Calm to light and variable surface wind conditions typically prevail over the Monterey Bay area during these nighttime hours. This lack of observation period did not interfere with the stratus investigation as the effect of the low level stratus on the resultant Monterey Bay sea-breeze was investigated during sea-breeze (daylight) hours.

IV. TEMPORAL FLUCTUATIONS IN AMBIENT WIND INTENSITY

Diurnal fluctuations in the wind speed intensity of a sea-breeze are primarily the result of cross-coast pressure gradient variations that arise from differential surface heating. Important modifying influences include the background synoptic-scale pressure pattern, static stability in the boundary layer, boundary layer depth, and clouds, all of which are typically related to the prevailing **synoptic-scale** situation. The goal of the present section is to examine these factors for the characteristic synoptic regimes of the California region.

A. RIDGE REGIME

The ambient wind variation in this regime is characterized by both diurnal speed and direction changes as shown by Case #1 which is depicted in Fig 14. Case 1 (May 14/06Z - 15/06Z) exemplified the influence of the ridge regime on the intensity of the ambient wind (Fig 15). During the first period, 06Z-18Z (2300-1100 PST), the wind was light & variable becoming 07 kts from the southeast at 13Z presumably due to terrain influences, finally becoming northwest by 16Z (0900 PST). The southeasterly nighttime wind direction was probably due to the cool drainage winds down the valley that lies to the east-southeast of Monterey airport (Fig 1). During the

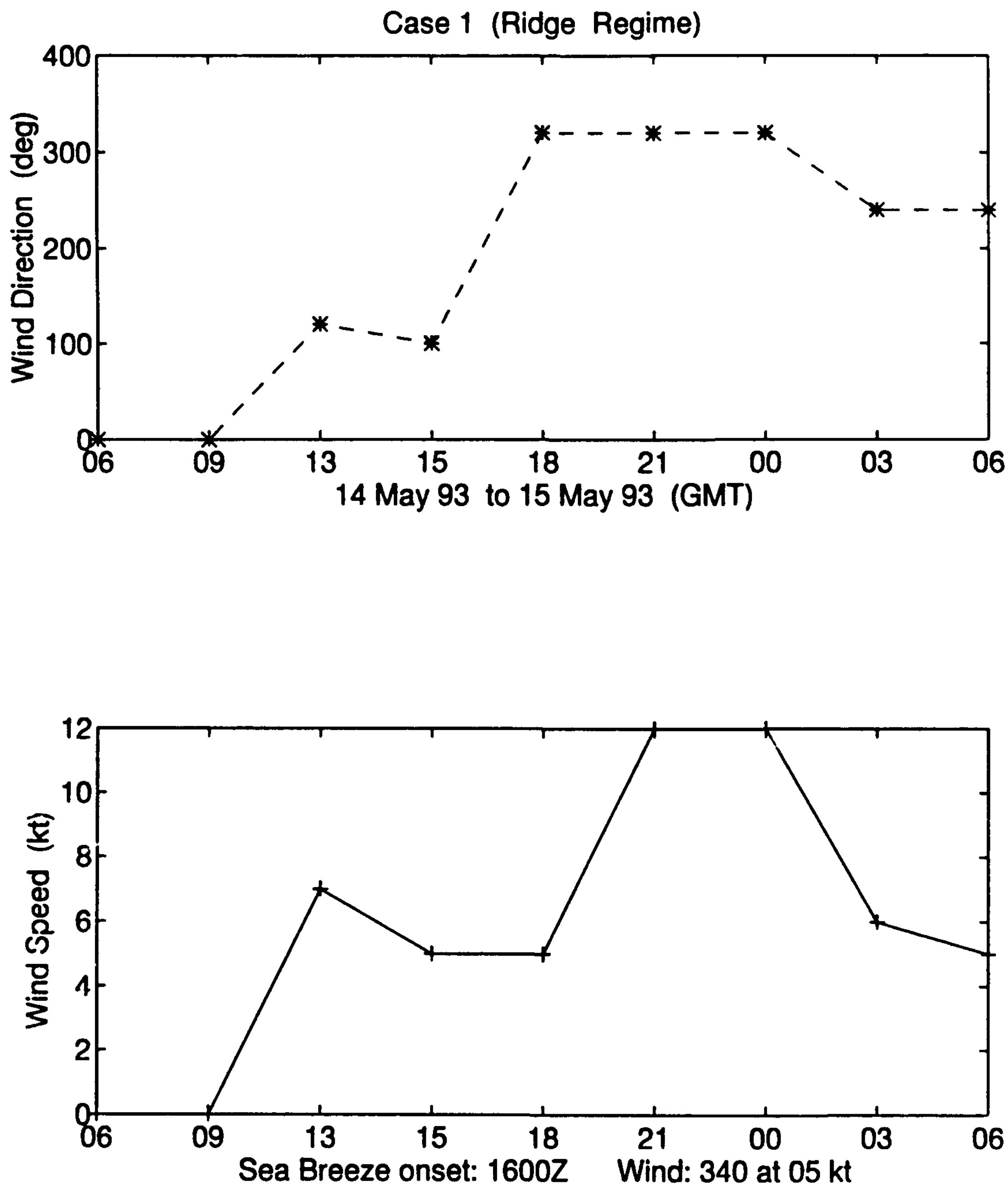


Figure 14. Case #1 wind speed & direction comparison.

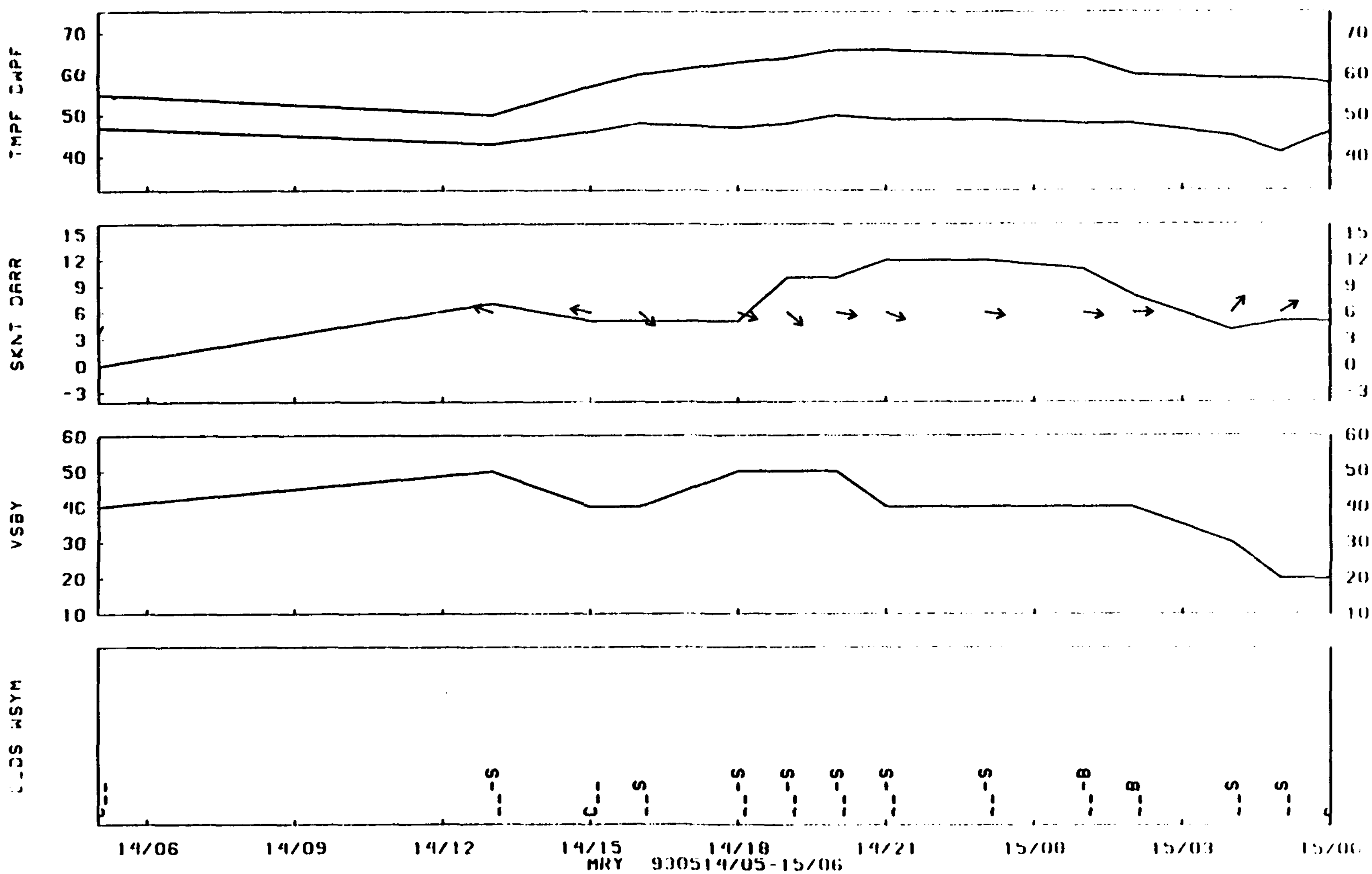


Figure 15. Time series of Case #1 for May 14/06Z - 15/06Z 1993.

second period, 18Z-03Z (1100-2000 PST), the wind was primarily northwesterly 07-12 kts steadily increasing to 12 kts at 00Z, then rapidly decreasing afterward. Finally, the third period, 03Z-06Z (2000-2300 PST), the wind was southwesterly 04-06 kts under the influence of the Eastern Pacific semi-permanent high pressure system centered southwest of Monterey.

Fig 16 indicates a relatively close relationship between the change in wind intensity and the corresponding cross-coast sea-level pressure difference. The weak pressure difference between 06Z (2300 PST) and 15Z (0800 PST) was 1-2 mb and corresponds to winds less than 07 kts. The increasing pressure difference (2.5-3.5 mb) between 18Z and 00Z corresponds to increasing winds (7-12 kts) as well. After 00Z, a relatively strong pressure difference persists (4.0 mb) but the winds drop from 12 kts to 6 kts (Fig 16). Although the correlation is not exact, this indicates that the pressure difference variations are not significantly modified by other factors for this regime, except for the period after 00Z (1700 PST) when the daytime surface heating rapidly decreases.

One possible explanation for the reduced wind speed dependence on the pressure gradient after 00Z may be the **boundary layer stability**. The Oakland (OAK) 12Z vertical atmospheric profile during the first period 06Z-18Z exhibited a relatively deep planetary boundary layer, approximately 925 mb, with a 2 deg C surface temperature inversion (Fig 17). The 00Z vertical profile during the second period 18Z-03Z

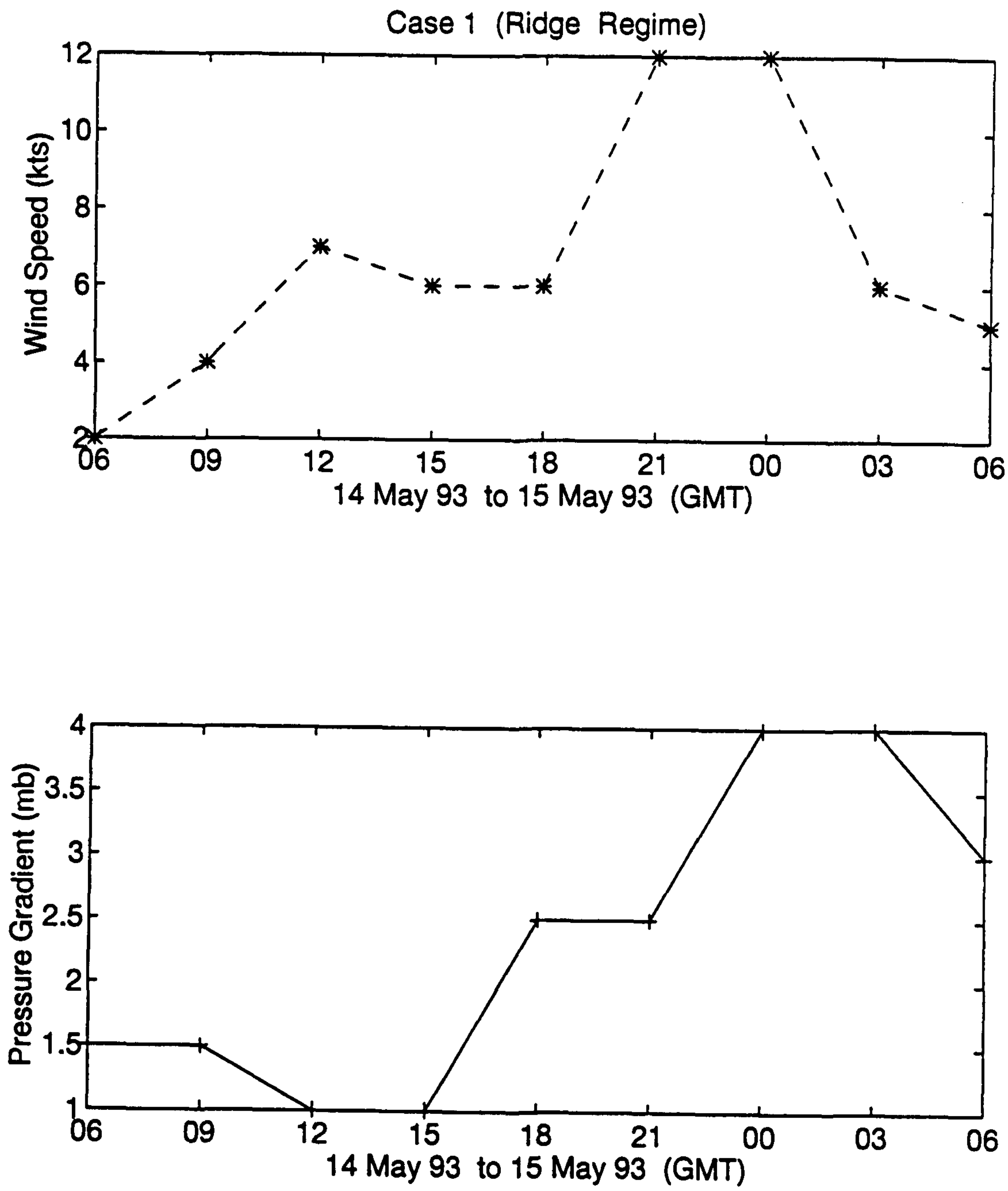


Figure 16. Case #1 wind speed - vs - pressure gradient comparison.

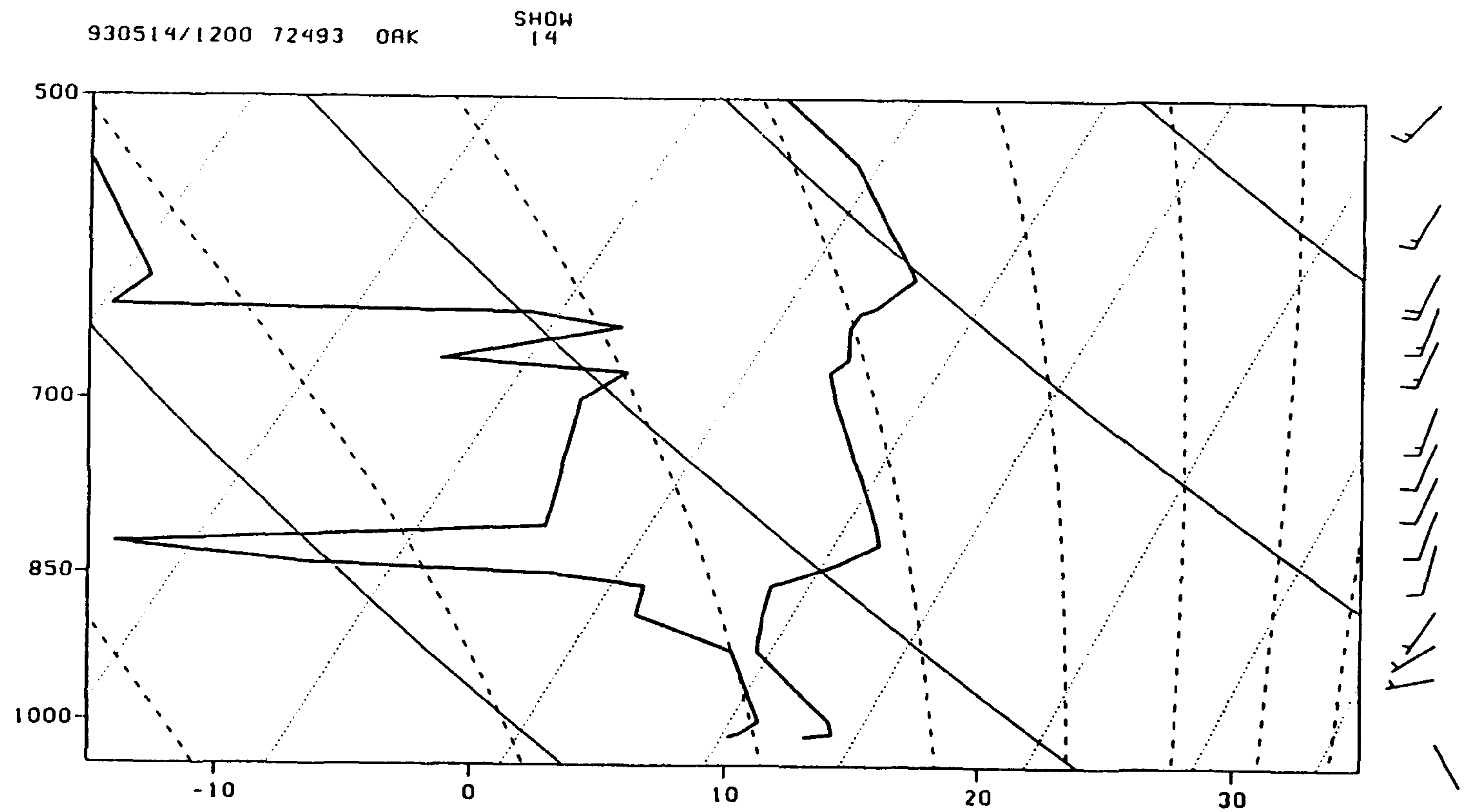


Figure 17. Oakland atmospheric sounding for May 14, 1993 at 12Z.

reflected a raising of the boundary layer inversion to approximately 900 mb and the surface inversion dissipated (Fig 18) to produce a maximum surface ambient wind speed of 12 kts at 21Z & 00Z (Fig 15). The planetary boundary layer shallowed during the third period 03Z-06Z to approximately 950 mb and a stronger surface inversion (5 deg C) was reestablished (Fig 19) by 12Z the following morning.

The relative **strength** of the surface **inversion** seems to directly correspond to the resultant surface ambient wind intensity. The presence of a surface temperature inversion corresponded to significantly weaker ambient winds, while a weak or non-existent surface inversion allowed for greater vertical mixing which corresponded to significantly stronger surface ambient winds, on the order of 4-6 kt stronger (Table 3). This indicates that the **coupling** of the **winds** above and below the surface layer can produce an extremely strong diurnal wind speed **enhancement**. In fact, the strong surface inversion appears to completely decouple the surface layer

Time (Z)	P - Gradient (mb)	Wind Speed (kts)	Boundary Layer Height (mb)	Oakland Sounding
0600 - 1800	1.0 - 2.5	02 - 07	925	14/12Z
1800 - 0300	2.5 - 4.0	07 - 12	900	15/00Z
0300 - 0600	0.5 - 4.0	04 - 06	950	15/12Z

Table 3. Case #1: pressure gradient, wind speed & marine boundary layer height comparisons.

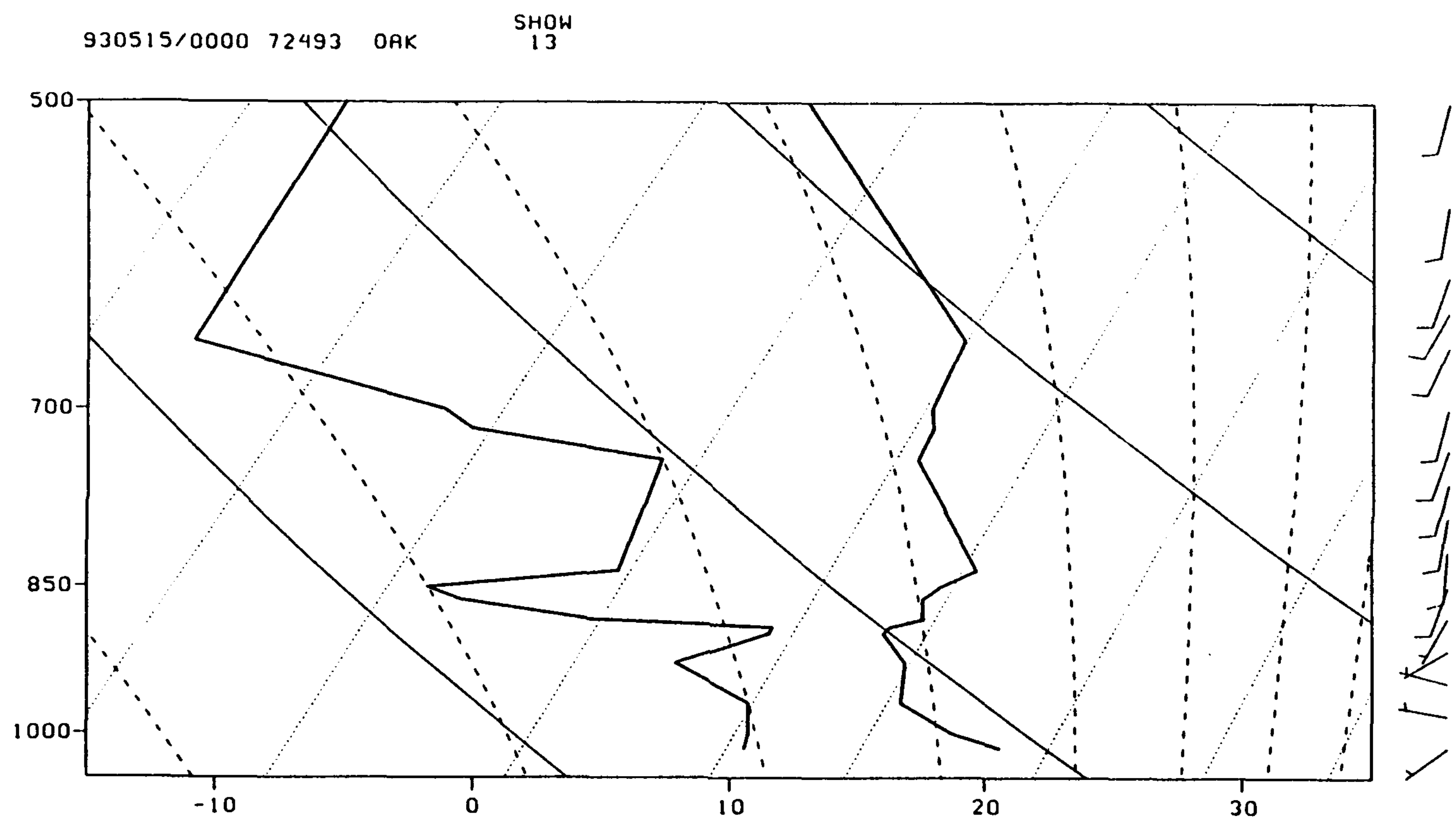


Figure 18. Same as 18 for 15 May 1993 at 00Z.

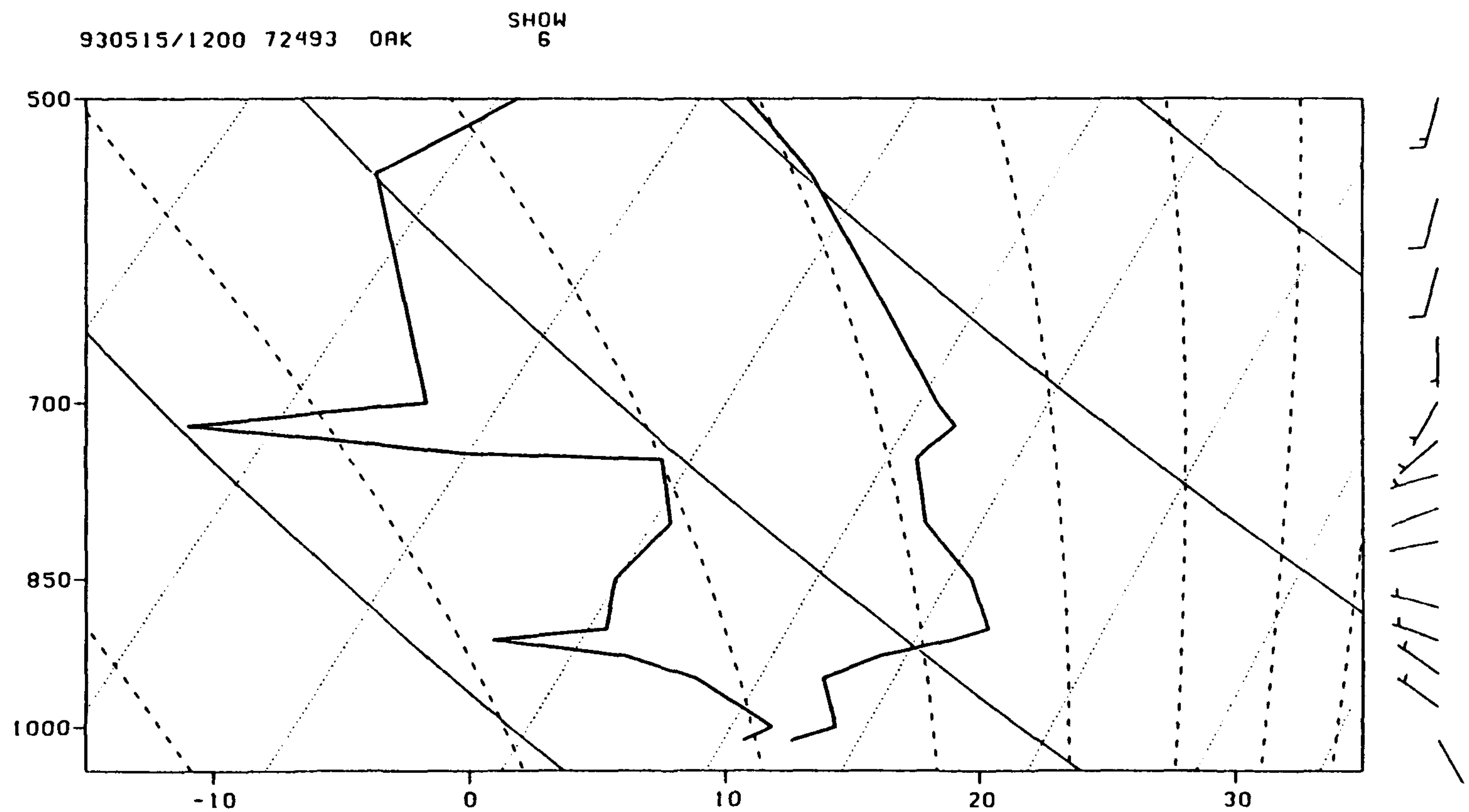


Figure 19. Same as 18 for 15 May 1993 at 12Z.

from the 4 mb pressure gradient at the end of case #1. These findings are consistent with the studies of Bridger et al., (1993) and Wexler (1946), where the rising of the marine boundary layer allowed greater vertical mixing with the California low-level coastal jet resulting in increased surface winds.

Comparing the analysis at the time of maximum winds of this strong sea-breeze day during case #1 (Fig 20) to the mean ridge pressure pattern over the region (Fig 2), it is clear that 2100Z 14 May has a stronger than normal pressure gradient for this ridge regime. Fig 2 illustrates the mean ridge pressure pattern having a 1.0 mb pressure gradient over the Monterey Bay area (approximately 275 km). Fig 20 depicts a 2.5 mb pressure gradient over Monterey Bay area translating to peak surface ambient winds of 12 kts (Fig 15).

Although Round (1993) suggests that **stratus** plays a role in the variability of the intensity of the ambient wind, this case did not have low-level clouds at all. Consequently the diurnal heating was not modified by marine stratus. High clouds were prevalent but varied only slightly over the 24 hour period and may not have produced a diurnal impact on the heating (Fig 15). However, the higher cloud cover may have resulted in lower maximum wind speeds than if conditions were clear.

Using Round's (1993) six sea-breeze characterizations (no sea breeze, gradual development, clear onset, frontal, double

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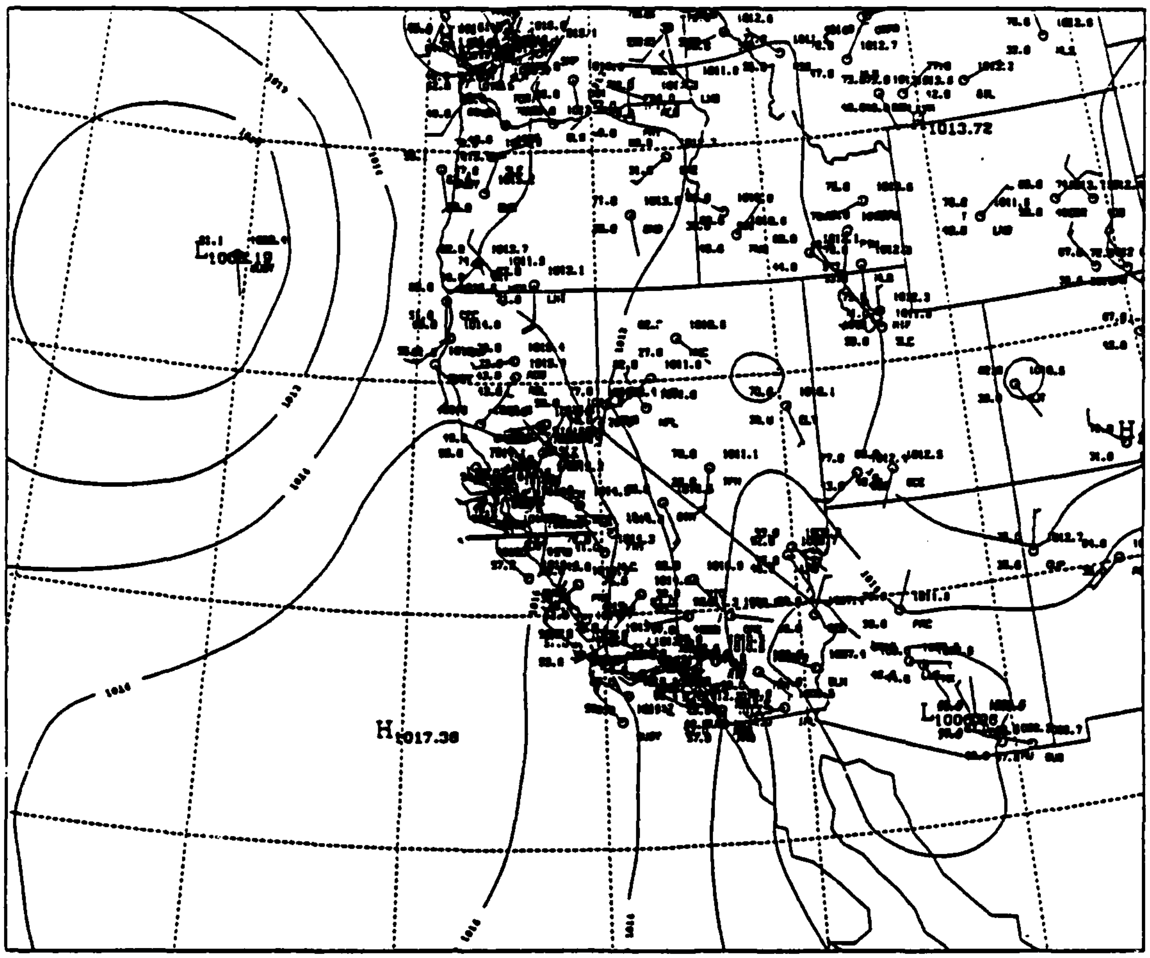

CONTOUR FROM 1008 TO 1016 BY 2

Figure 20. Surface pressure analysis for May 14, 1993 at 21Z

surge, and unclassifiable), this case fits the characterization of the clear onset type sea-breeze. There was a definite wind shift in case #1 from 100 deg to 320 deg at 16Z (0900 PST), but the ambient wind did not significantly increase until after 19Z (1200 PST). As defined by Round clear onset type sea-breezes occurred with either:

i) a definite wind shift without a significant wind speed increase, or

ii) onshore conditions prevailing prior to sea-breeze onset distinguished by a distinct increase in onshore wind speed.

B. TROUGH REGIME

The ambient wind variation in this regime is characterized predominantly by diurnal wind speed changes with little directional change as shown by cases #3 & #6 depicted in Figs 21 & 22 respectively. Both cases reflect nearly calm wind conditions prior to sea-breeze onset. Dividing these time series into periods similar to case #1, the 06Z-18Z period of case #3 (June 08/06Z - 09/06Z) exhibited winds varying between north and northwest 02-08 kts while the same period of case #6 (June 19/06Z - 20/06Z) exhibited winds predominantly calm until 17Z (0900 PST) when the wind became north-northwest at 05 kts. Winds during the 18Z-03Z period of case #3 were predominantly northwest 08-15 kts, peaking at 15 kts at 20Z (1300 PST), then rapidly dropping off. During case #6, the winds in the 18Z-03Z period were predominantly westerly

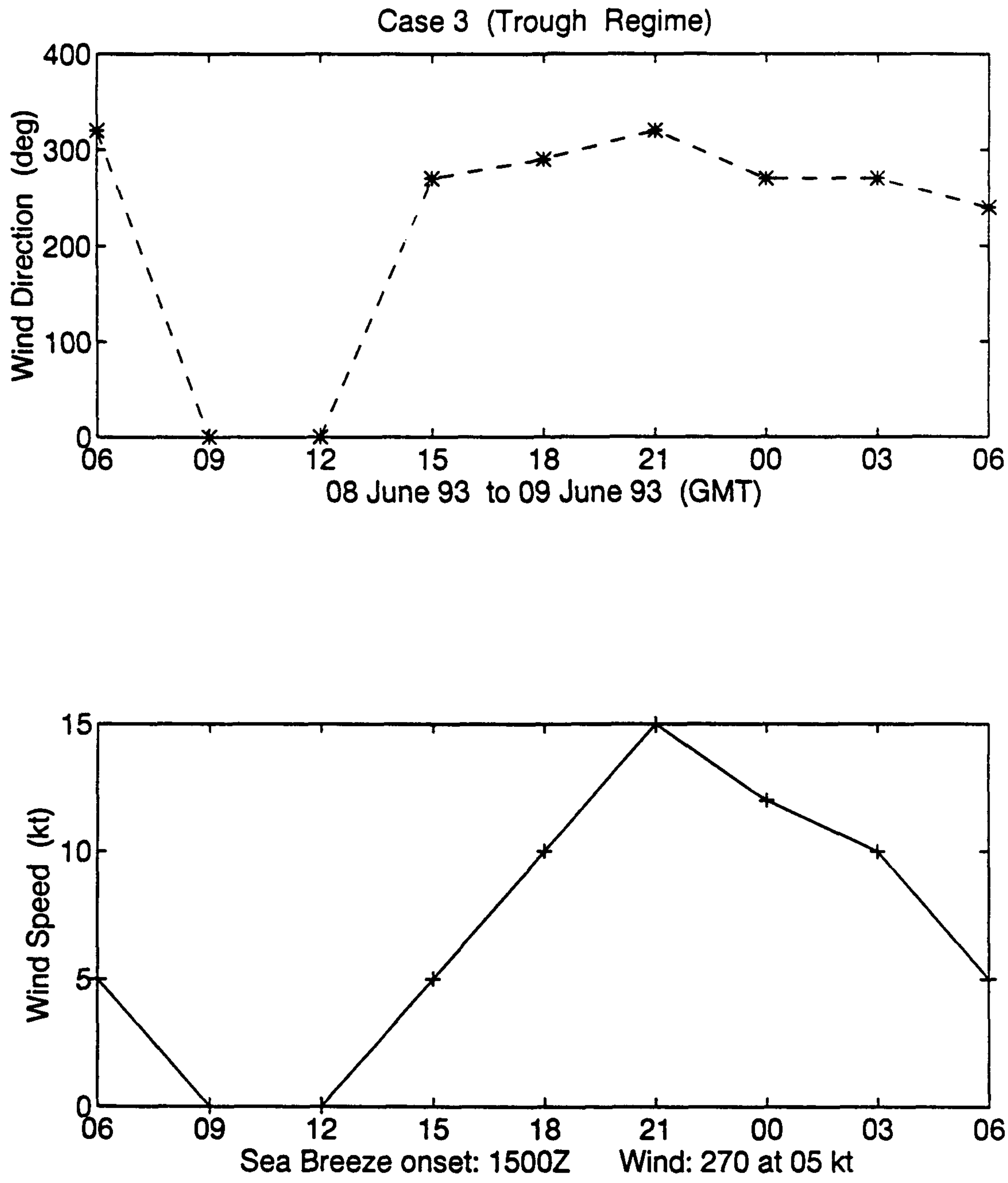

Figure 21. Case #3 wind speed - vs - direction comparison.

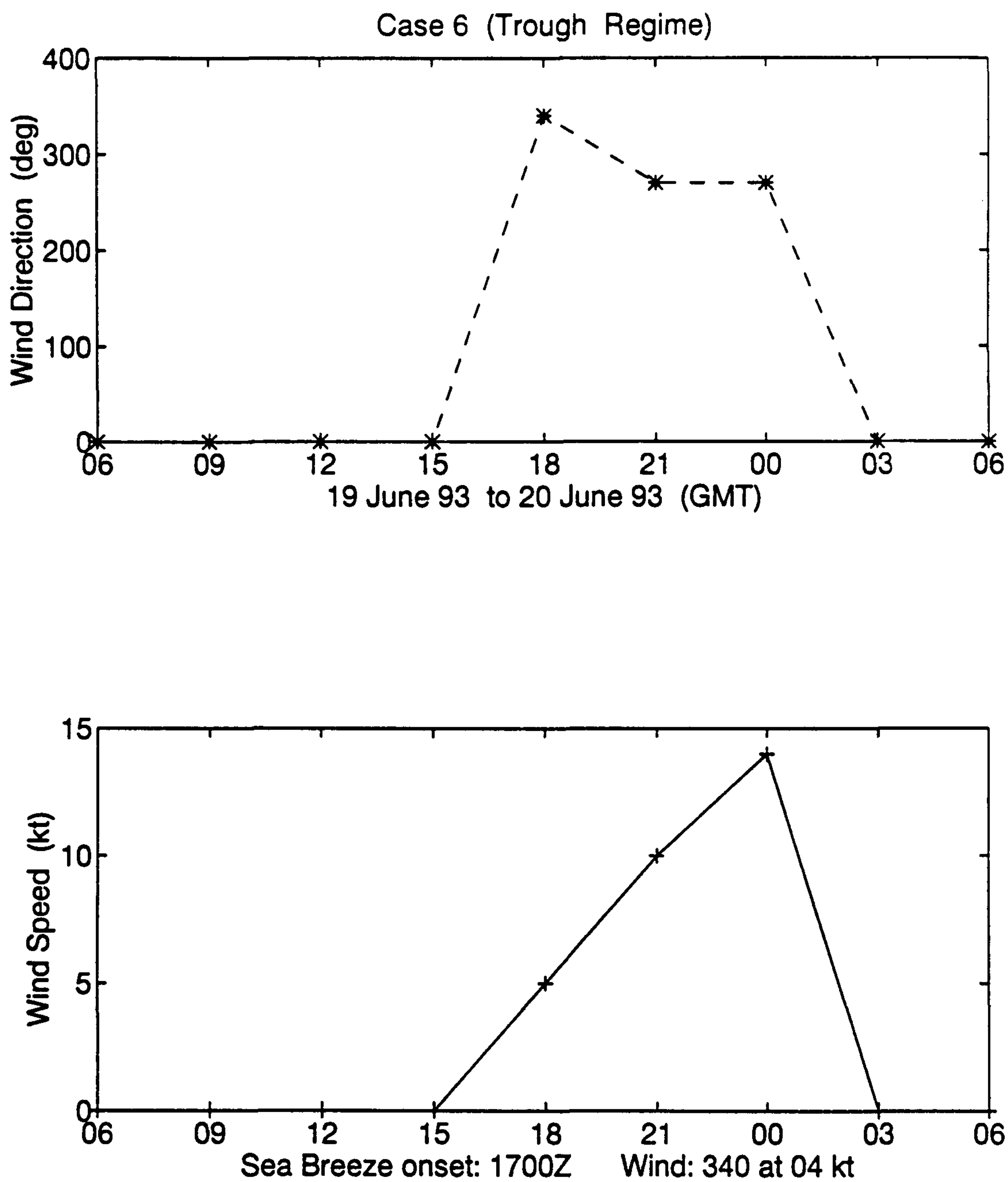

Figure 22. Case #6 wind speed - vs - direction comparison.

increasing from 5 kts at 18Z to 13 kts at 00Z, then dropping off to 05 kts by 03Z (2000 PST). Finally, the winds of the 03Z-06Z period of case #3 varied between west and southwest 05-08 kts while during case #6 they were initially westerly 05 kts dropping to calm at 06Z.

After onset for both cases (#3 & #6), the winds immediately become westerly or northwesterly with the wind speed steadily increasing for the 8-9 hours following onset. This **clear onset type** sea-breeze, which is presumably increasingly influenced by the coastal heating as the day progresses, results in a significant wind speed enhancement through the thermal wind relationship. Sea-breeze onset for case #3 occurred at 15Z (0800 PST), when the wind shifted from calm to 270 deg at 05 kts. The sea-breeze onset for case #6 occurred at 17Z (1000 PST), with the wind shifting from calm to 340 deg at 05 kts. A gradual ambient wind speed increase occurred throughout case #3 until the winds began to decrease after 22Z (1500 PST). During case #6 the wind speed gradually increased to 13 kts by 00Z (Figs 23 & 24).

Figs 25 & 26 depict a lack of correlation between the pressure gradient and the resultant ambient wind speed intensity until sea-breeze onset occurs, when a large pressure difference corresponds to higher surface wind speeds. The pressure gradient varies less than 2 mb over the 24 hour period with generally a weaker gradient from 06Z to 15Z for both cases. The one exception to this is the 1 mb pressure

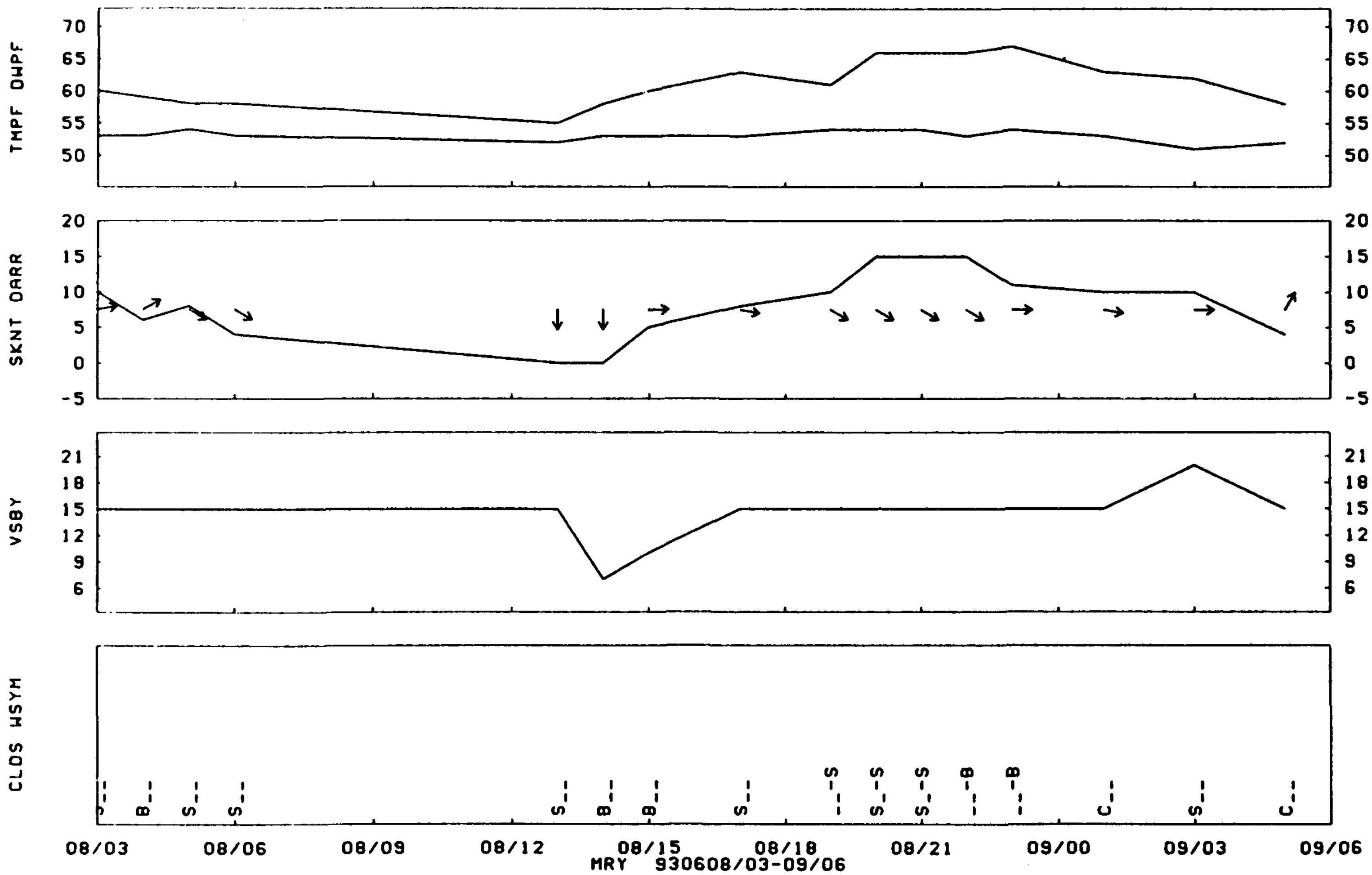

Figure 23. Time series of case #3 for June 08/03Z-09/06Z 1993.

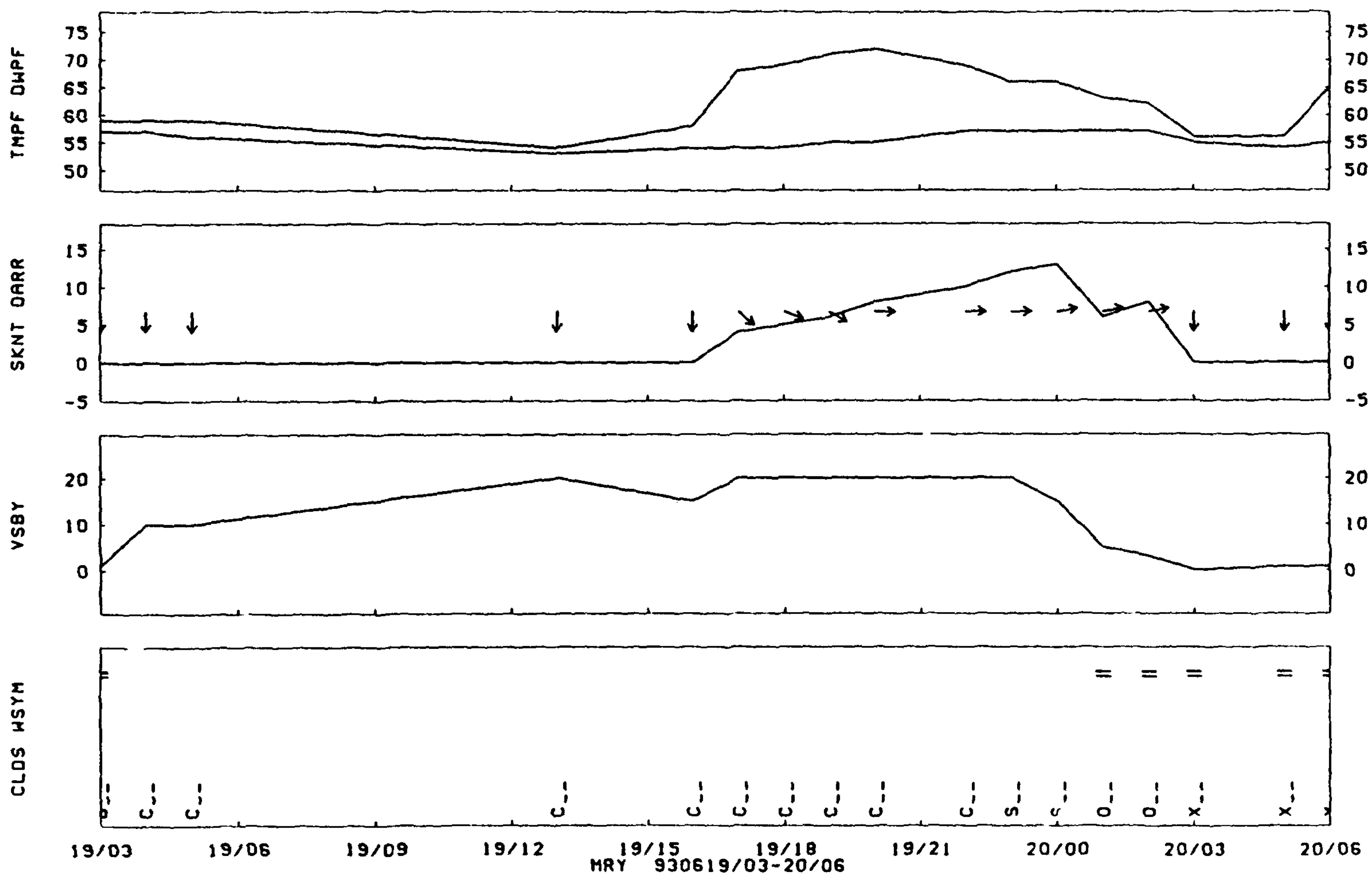

Figure 24. Time series of case #6 for June 19/03Z-20/06Z 1993.

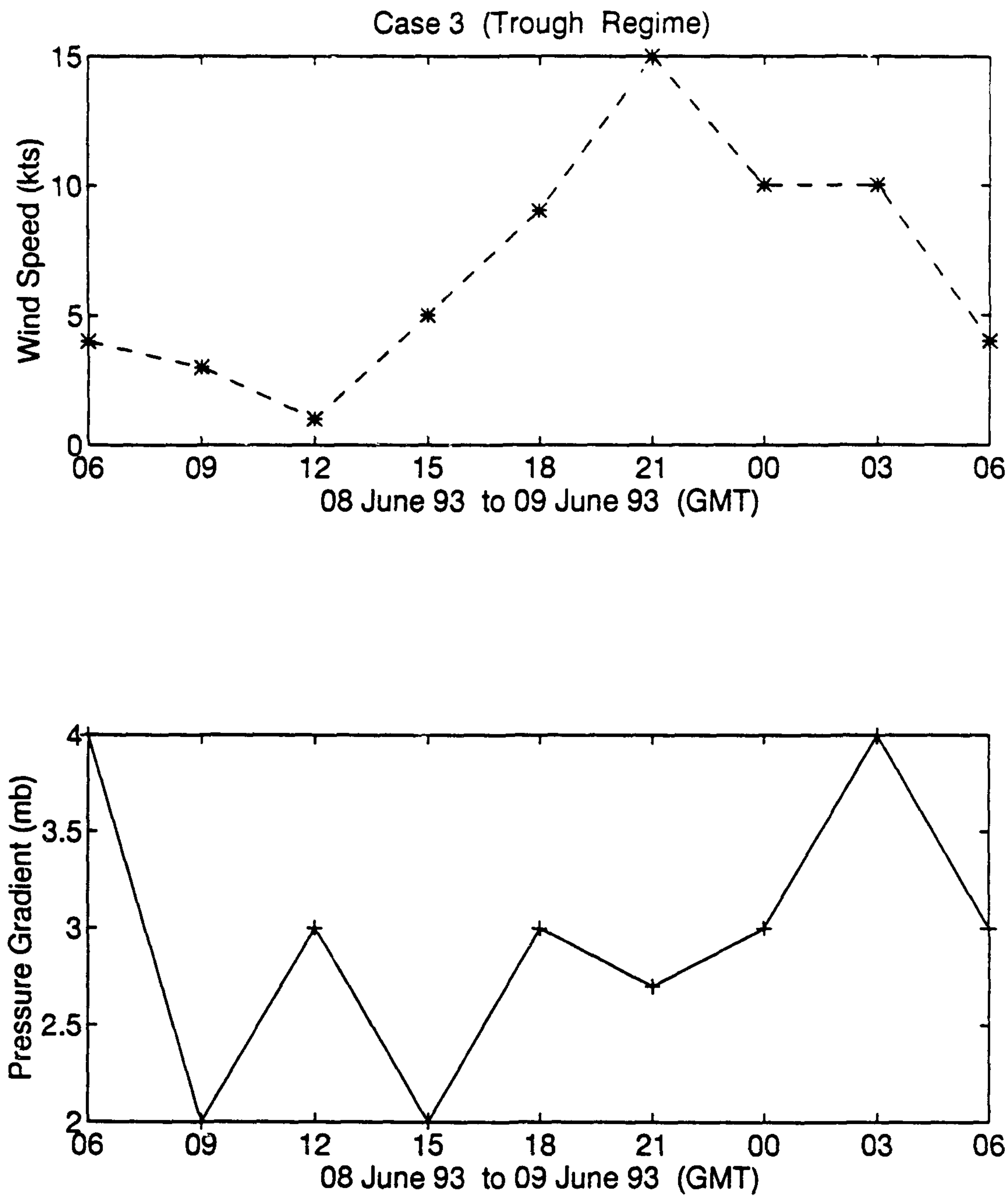

Figure 25. Case #3 wind speed - vs - pressure gradient comparison.

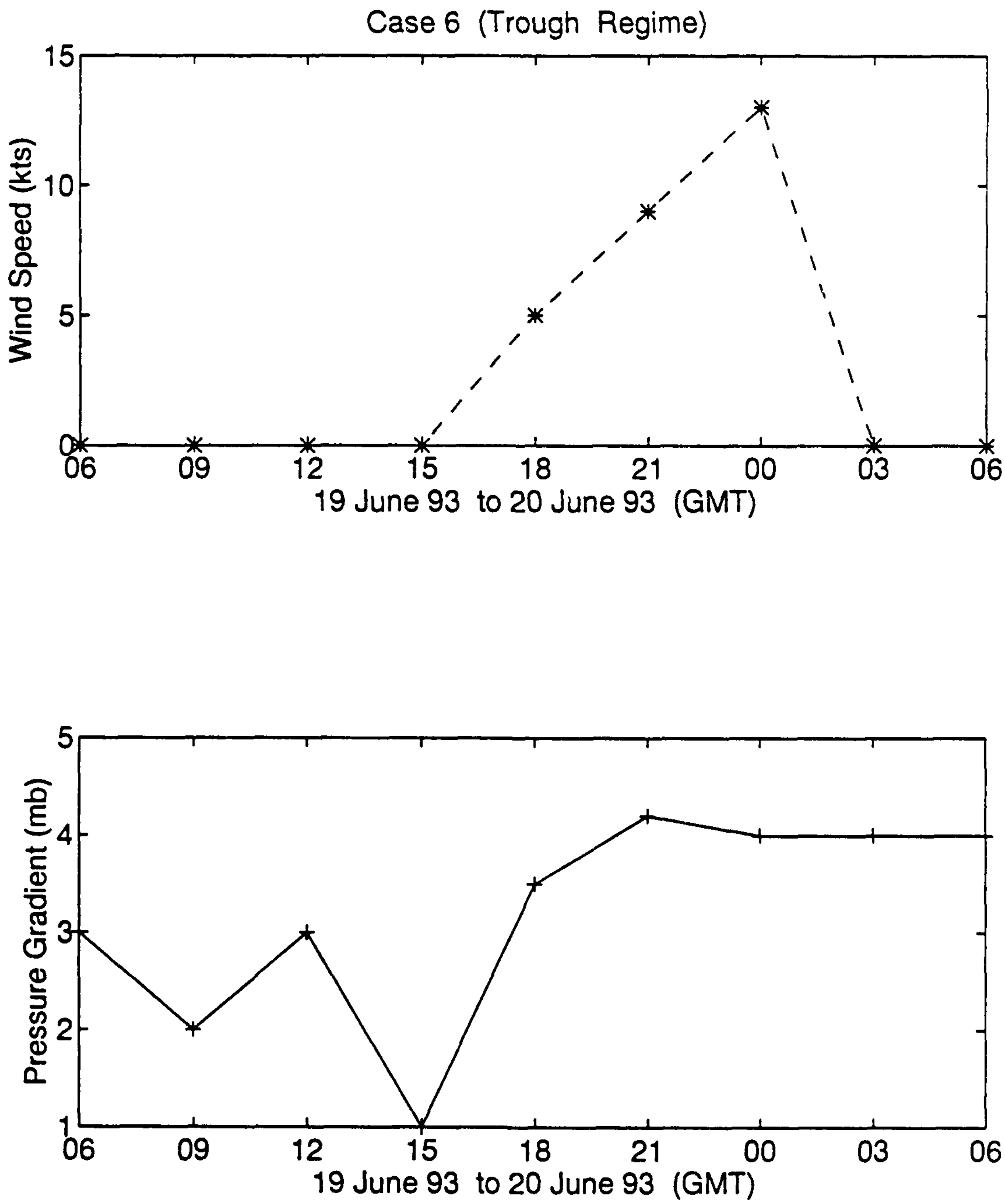

Figure 26. Case #6 wind speed - vs - pressure gradient comparison.

gradient at 15Z for case #6, which maybe due to inadequate analysis as few stations reported for that analysis time period. After 15Z the gradient tends to increase as expected with the falling pressures in the interior regions of California due to the daytime heating. After maximum winds are reached, the pressure gradient remains large but the winds begin to decline. The amplitude of the diurnal pressure gradient variation was typically less than 2 mb for these cases, which does not alone explain the 10 kt or greater wind variation given that the pressure gradient occurs over a distance of approximately 275 km.

The boundary layer **depth** and **stability** were investigated to assess their potential influence on the temporal wind fluctuations in the two trough cases. The 12Z atmospheric vertical profile for the first period of case #3 (06Z-18Z) had a relatively shallow boundary layer (950 mb) with a moderately strong (2 deg C) surface inversion (Fig 27). The inversion at the planetary boundary layer top, although relatively strong, was not the typical subsidence inversion which is evident above 700 mb. The 12Z sounding for the first period of case #6 exhibited a shallower boundary layer (990 mb) with a distinct 14 deg C subsidence inversion that originates from the surface (Fig 28). The 00Z sounding for the second period of case #3 (18Z-03Z) exhibited a deepening boundary layer (900 mb), a 4 deg C superadiabatic surface layer, and the subsidence inversion has lowered to 775 mb (Fig 29). During

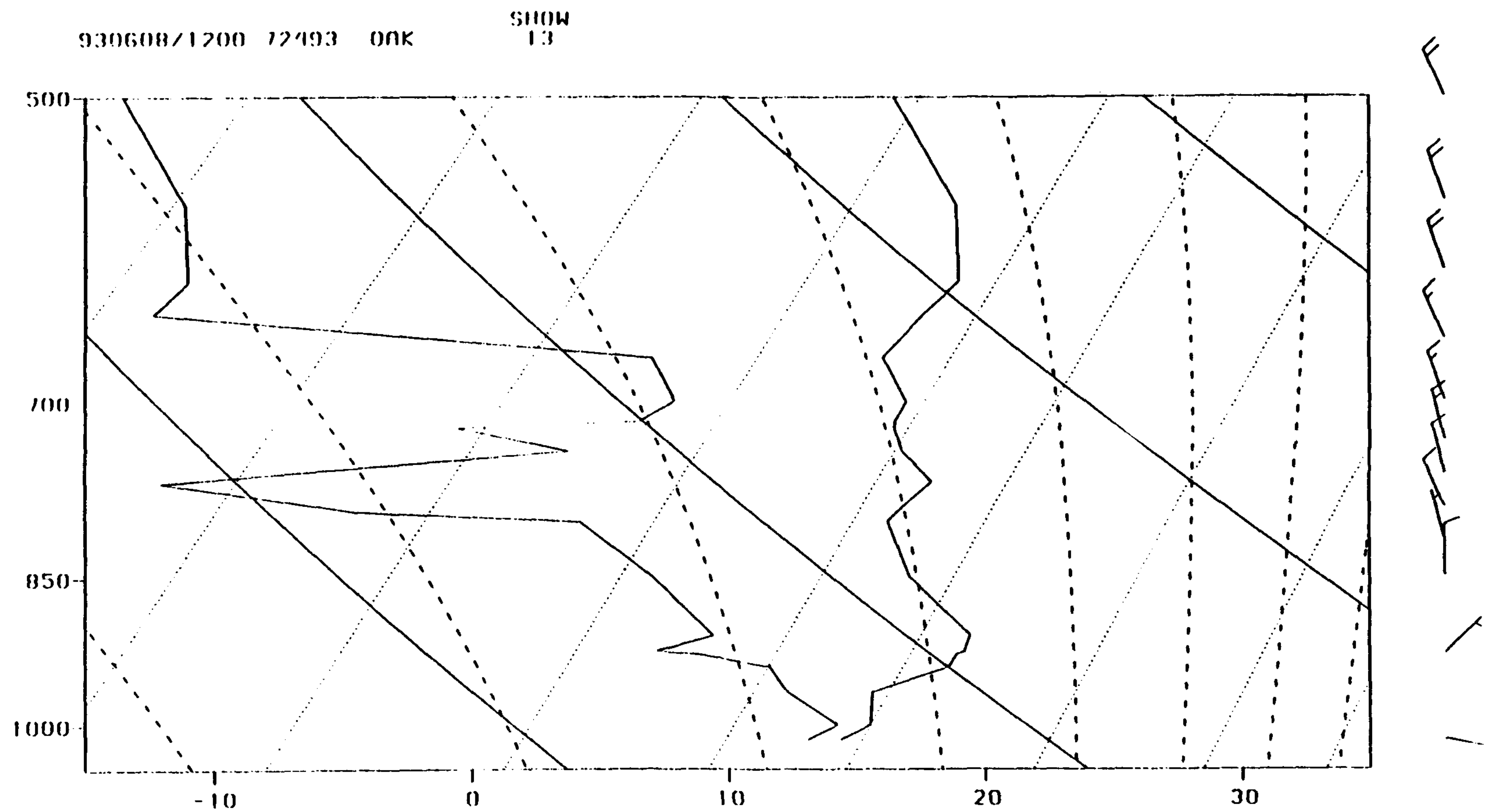

Figure 27. Oakland atmospheric sounding for June 08 1993 at 12Z.

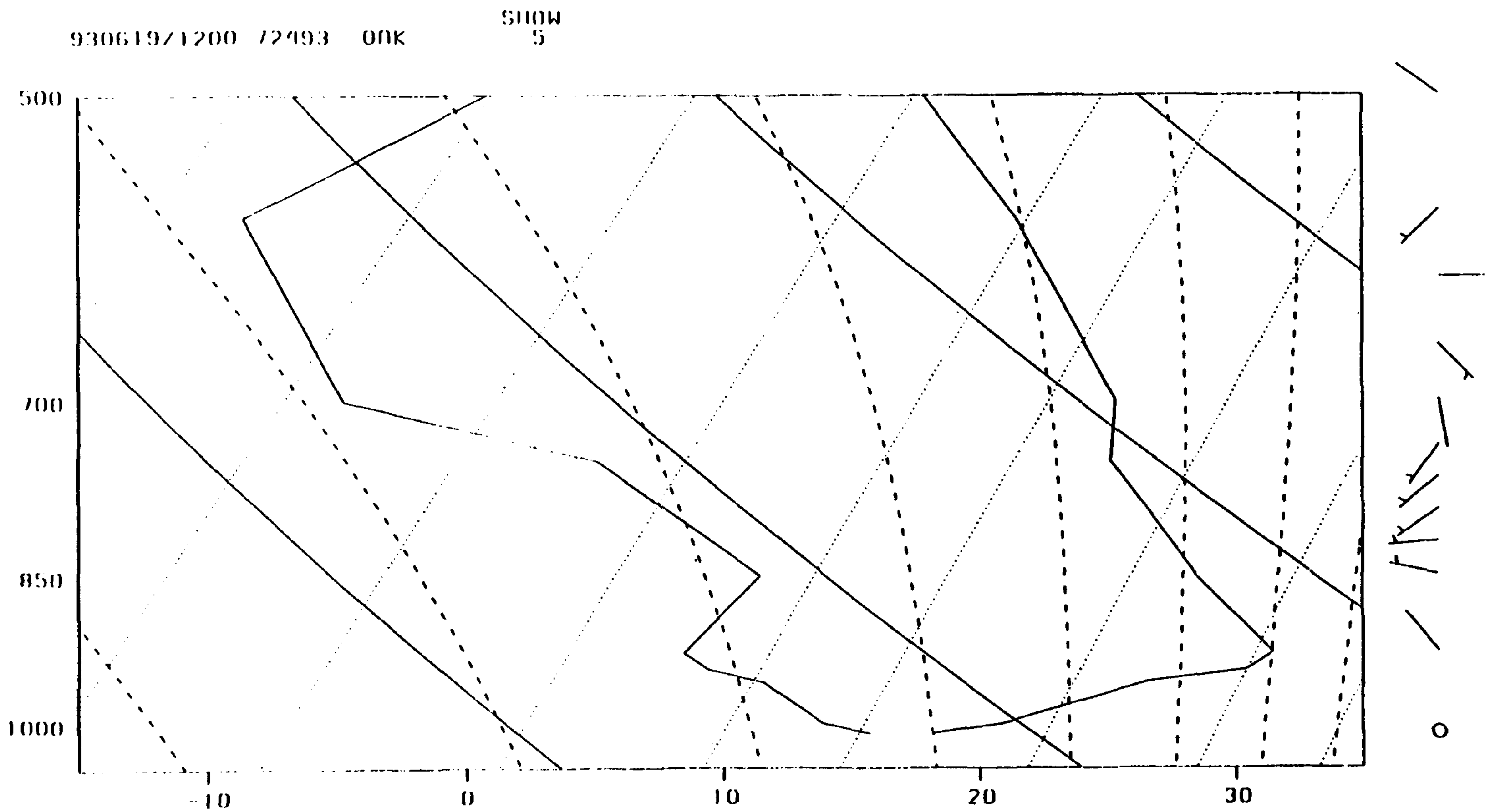

Figure 28. Oakland atmospheric sounding for June 19 1993 at 12Z.

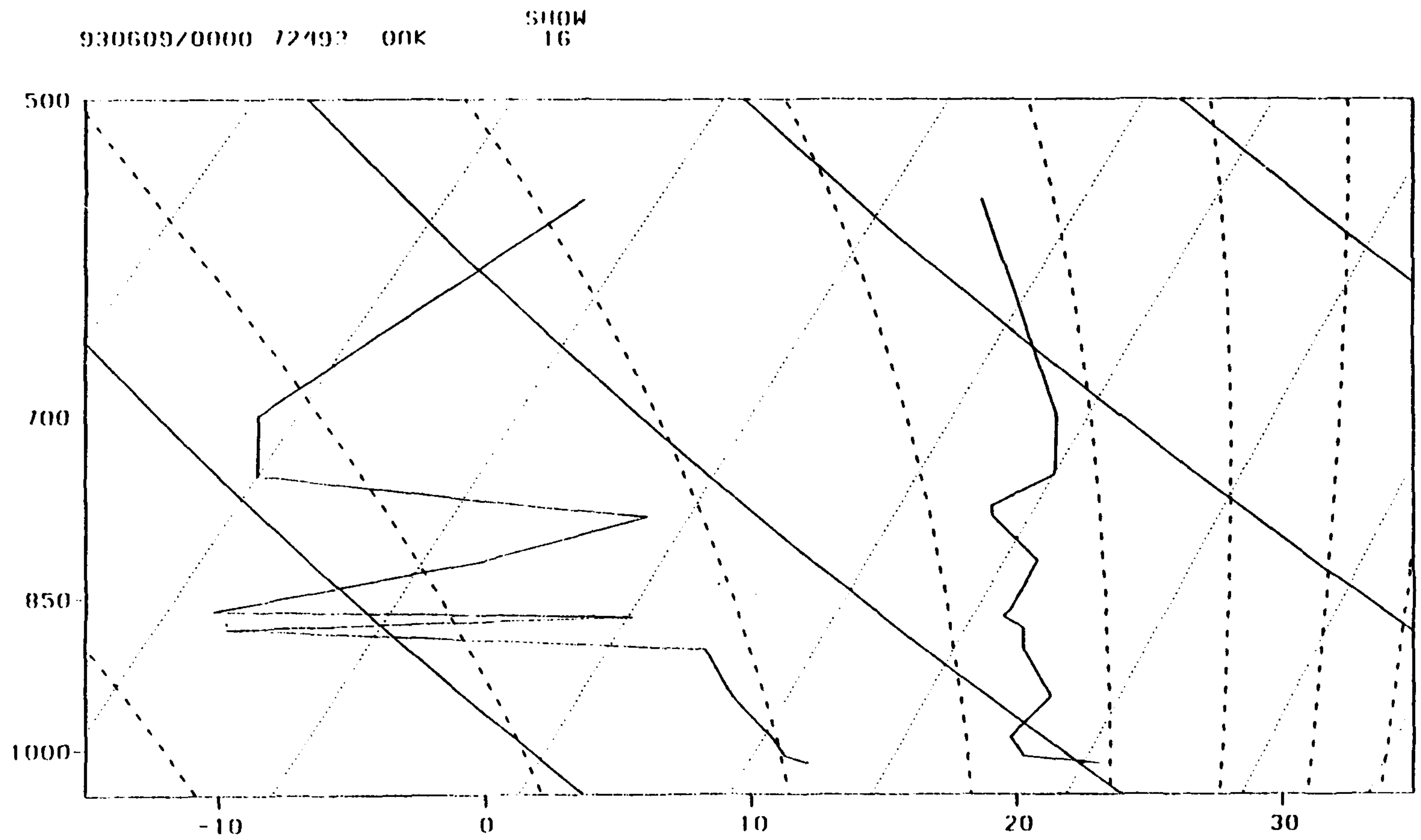

Figure 29. Oakland atmospheric sounding for June 09 1993 at 00Z.

the second period of case #6 the strong subsidence inversion evident at 12Z had weakened by 00Z (Fig 30). This weakening was due to the strong surface heating which had produced a 2.5 deg C superadiabatic layer. Finally, the 12Z sounding after the third period of case #3 (Fig 31) shows that a 2.5 deg C surface inversion develops overnight and the subsidence inversion has lowered to cap the boundary layer at 950 mb. The 12Z sounding after the third period of case #6 (Fig 32) shows that the subsidence capped boundary layer has lifted to approximately 970 mb and that only a weak (1 deg C) or non-existant surface inversion develops overnight. Case #3 contrasts with case #6 in that the marine boundary layer is developing under a lowering subsidence inversion whereas case #6 develops a distinct marine boundary layer from a well established surface based subsidence inversion.

As discussed above, the ambient wind variation during the Trough regime was basically uncorrelated with the pressure difference across the coast. However, the examination of the boundary layer stability shows that the **strongest** winds in both case #3 & case #6 occur once a **superadiabatic** surface layer has developed in response to the surface heating. When the surface cooled off and a surface inversion developed, the ambient winds were weak inspite of a very strong cross-coast pressure gradient. This suggests that the **primary** role of the coastal surface heating is to **weaken** the boundary layer **stability** and allow **mixing** of higher velocity air down to the

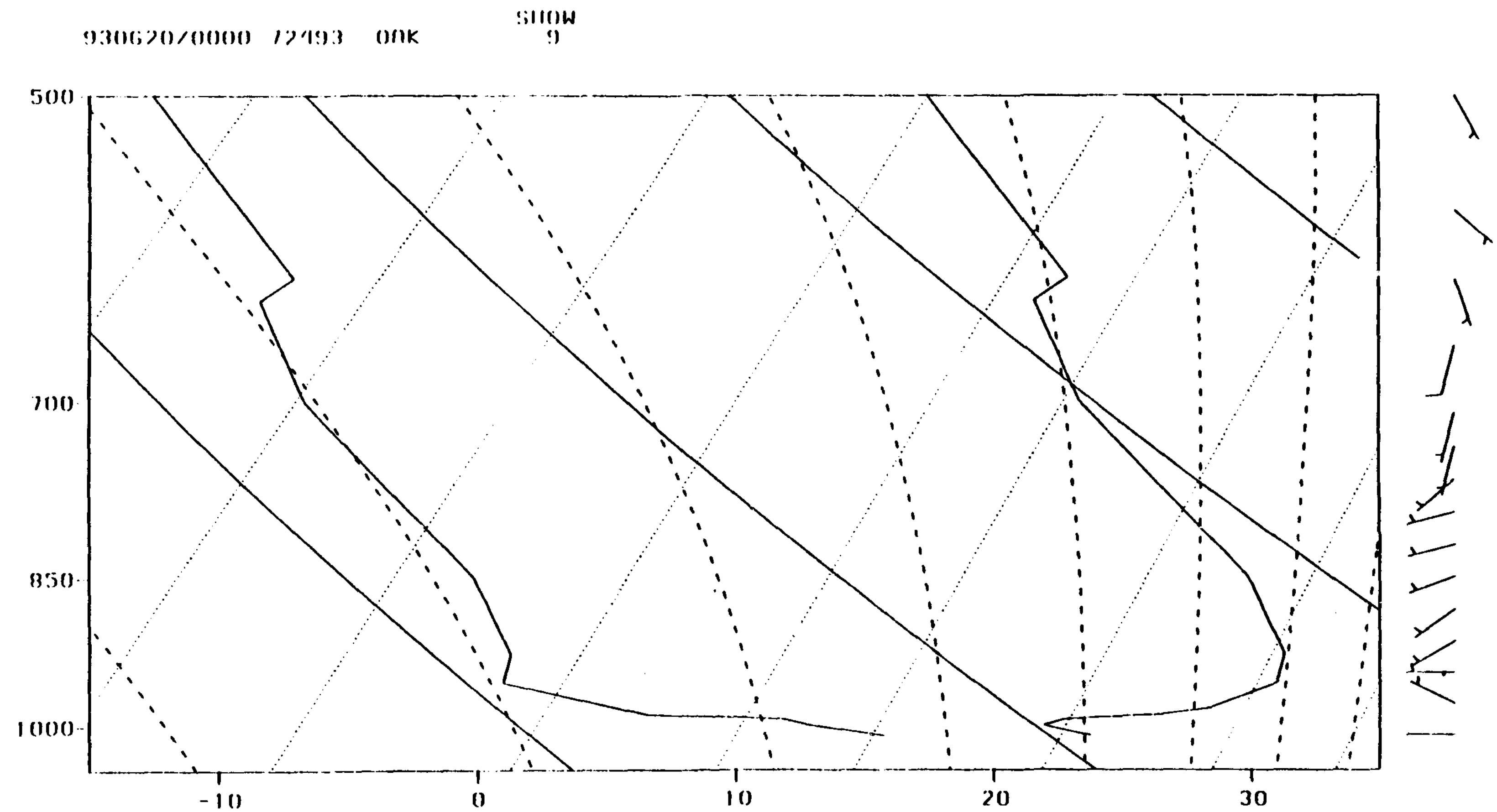

Figure 30. Oakland atmospheric sounding for June 20 1993 at 00Z.

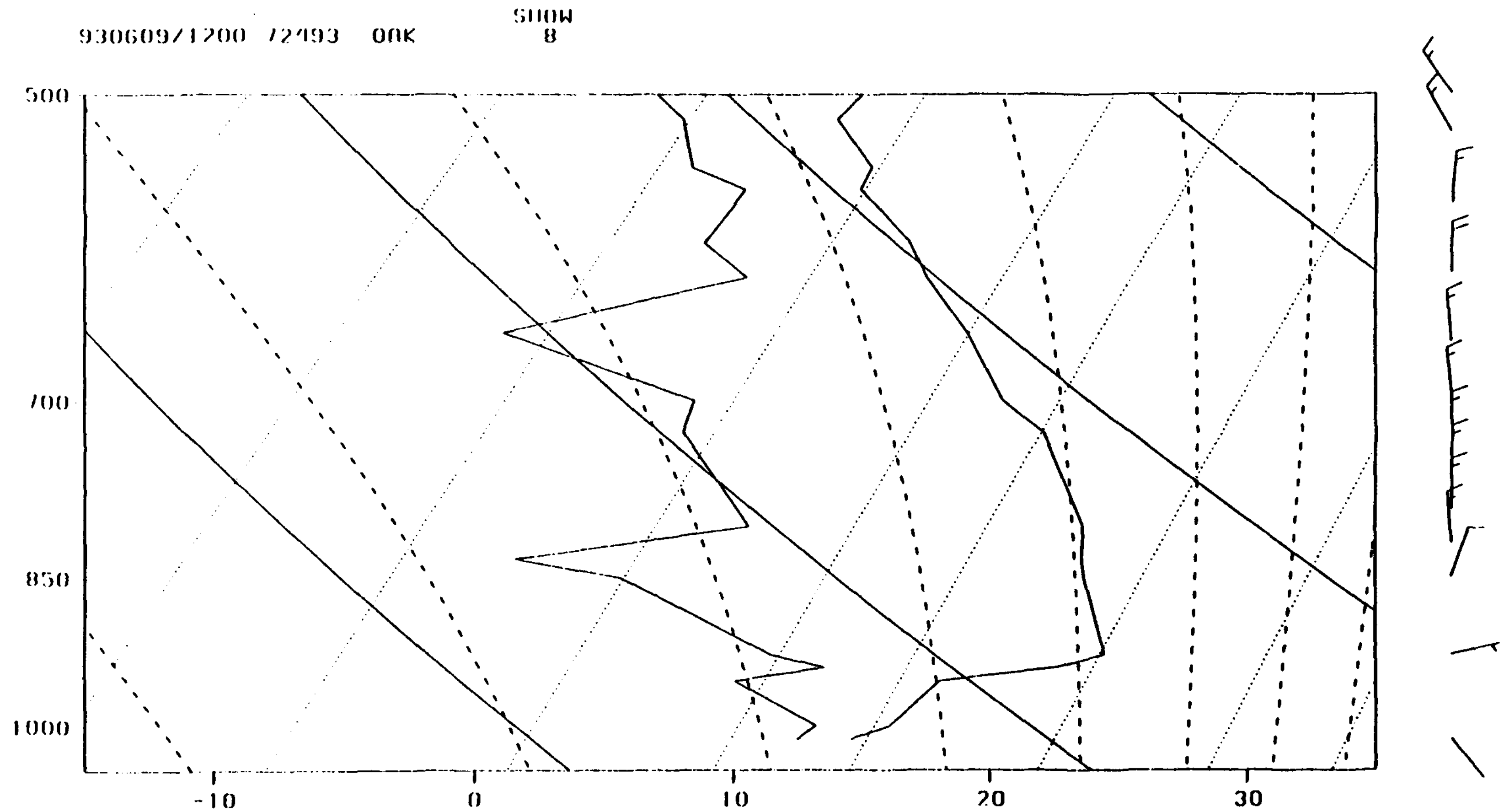

Figure 31. Oakland atmospheric sounding for June 09 1993 at 12Z.

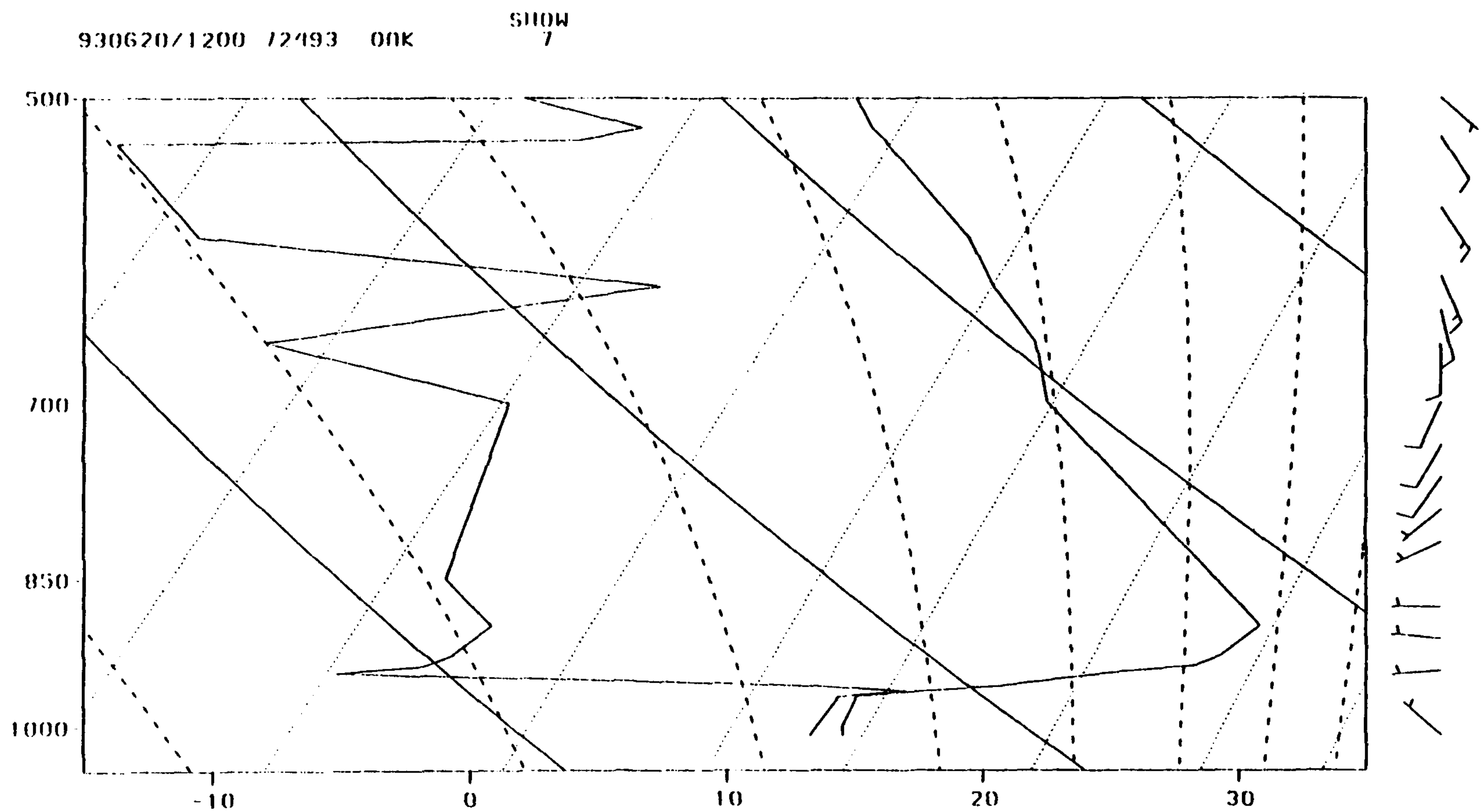

Figure 32. Oakland atmospheric sounding for June 20 1993 at 12Z.

surface, consistent with results from Beardsley et al., (1987). The apparent impact of the heating on the pressure gradient is very small, which contributes little to driving a cross-coast sea-breeze circulation. This is evident in the lack of wind direction changes that were noted above.

The role of **clouds** in modifying the sea-breeze in these two Trough cases is not clear and appears to be a **secondary** influence as the stratus pattern for these two cases (#3 & #6) was very different. For case #3 low clouds were evident throughout the day, while for case #6 clear conditions generally prevailed. In comparison to Round's (1993) findings, the generally clear conditions of case #6 should have amounted to a significantly greater increase in the resultant sea-breeze intensity. However, this was not the case. The range of wind speed for case #6 with little to no cloud cover was 0 to 13 kts (Table 4) as compared to case #3 with a significantly greater amount of low stratus cover and a range of wind speed of 2 to 15 kts (Table 5). Comparing the 18Z to 21Z time periods of both cases, case #3 with prevalent

Time (Z)	P - Gradient (mb)	Wind Speed (kts)	Boundary Layer Height (mb)	Oakland Sounding
0600 - 1800	1.0 - 4.0	00 - 05	990	19/12Z
1800 - 0300	3.5 - 4.2	05 - 13	Near Surface	20/00Z
0300 - 0600	3.0 - 4.0	00 - 05	970	20/12Z

Table 4. Case #6: pressure gradient, wind speed & marine boundary layer height comparisons.

Time (Z)	P - Gradient (mb)	Wind Speed (kts)	Boundary Layer Height (mb)	Oakland Sounding
0600 - 1800	2.0 - 4.0	02 - 08	970	08/12Z
1800 - 0300	3.2 - 4.0	08 - 15	900	09/00Z
0300 - 0600	1.5 - 3.0	05 - 08	950	09/12Z

Table 5. Case #3: pressure gradient, wind speed & marine boundary layer height comparisons.

low level stratus and case #6 with cirrus coverage, case #3 experienced stronger surface ambient winds (9-15 kts) than case #6 (6-9 kts) with no low-level clouds. The stratus influence in case #6 was most evident between 20/00Z and 20/03Z. The normal decrease of surface heating during this time of day and its effect on the ambient wind intensity was accelerated by the increase in the amount of low cloud cover. The period exhibited a rapid increase from scattered stratus to overcast with a resultant ambient wind speed intensity decrease from 13 kts to calm conditions (Fig 24). The stability of the atmosphere did not change noticeably between 19/12Z and 20/12Z for case #6, yet the variability of the stratus deck and the resultant fluctuations in surface heating resulted in dramatic variations in the intensity of the surface ambient wind. It appears that clouds play a secondary role of influence on the ambient wind variation during the heating of the day for the Trough regime. After 1700 PST when the surface temperatures begin to decline, the clouds appear to exert a more prominent influence on the surface ambient

to exert a more prominent influence on the surface ambient wind intensity.

Using Round's (1993) sea-breeze characterizations, these two trough regime cases are classified as **clear onset type** of sea-breezes. Both cases (#3 & #6) were near calm or calm until sea-breeze onset occurred with the wind from a persistent direction but light in intensity (Figs 23 & 24). The surface ambient winds gradually increased until maximum wind speed was attained before rapidly dropping off again.

Comparing the analysis at the time of maximum wind of the strong sea-breeze day during case #3 (Fig 33) to the mean trough pressure pattern over the region (Fig 3), it is clear that 1800Z 08 June has twice the mean pressure gradient for this trough regime. Fig 3 illustrates the mean trough pressure pattern having a 1.5 mb gradient over Monterey Bay while Fig 33 depicts a 3.0 mb pressure gradient over the region resulting in a maximum ambient wind of 15 kts for the 24 hour period. The 2100Z 19 June analysis at the time of maximum wind of the strong sea-breeze day during case #6 (Fig 34) compared to the mean trough pressure pattern over the region shows a significantly stronger pressure gradient over the Monterey Bay than the mean trough pressure gradient for the trough regime. Fig 34 depicts a 4.0 mb pressure gradient compared to the 1.5 mb of the mean (Fig 3) over the region resulting in the maximum ambient wind of 13 kts for the 24 hour period. Thus Case #6 had a stronger pressure gradient

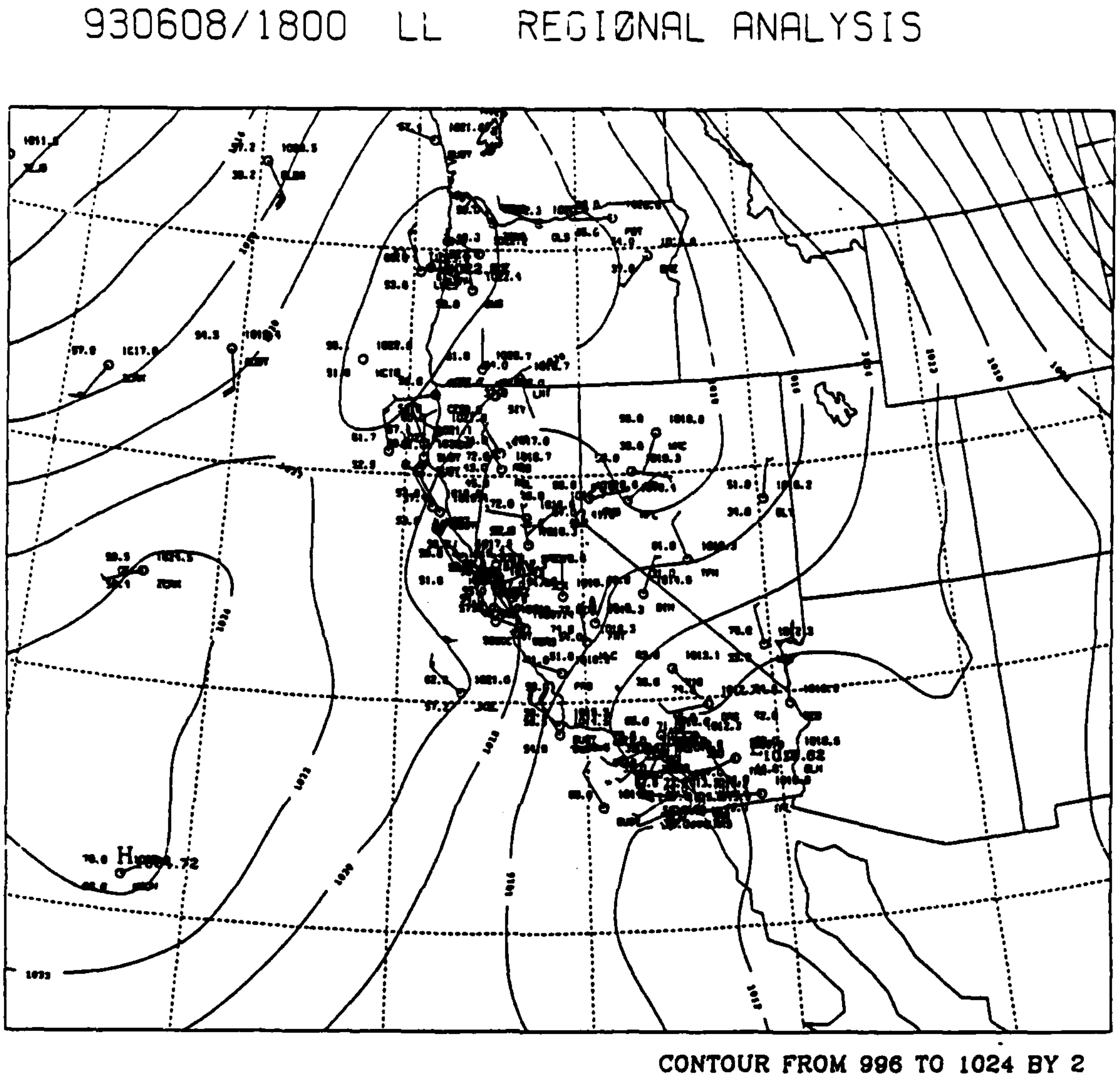

Figure 33. Surface pressure analysis for June 08 1993 at 18Z.

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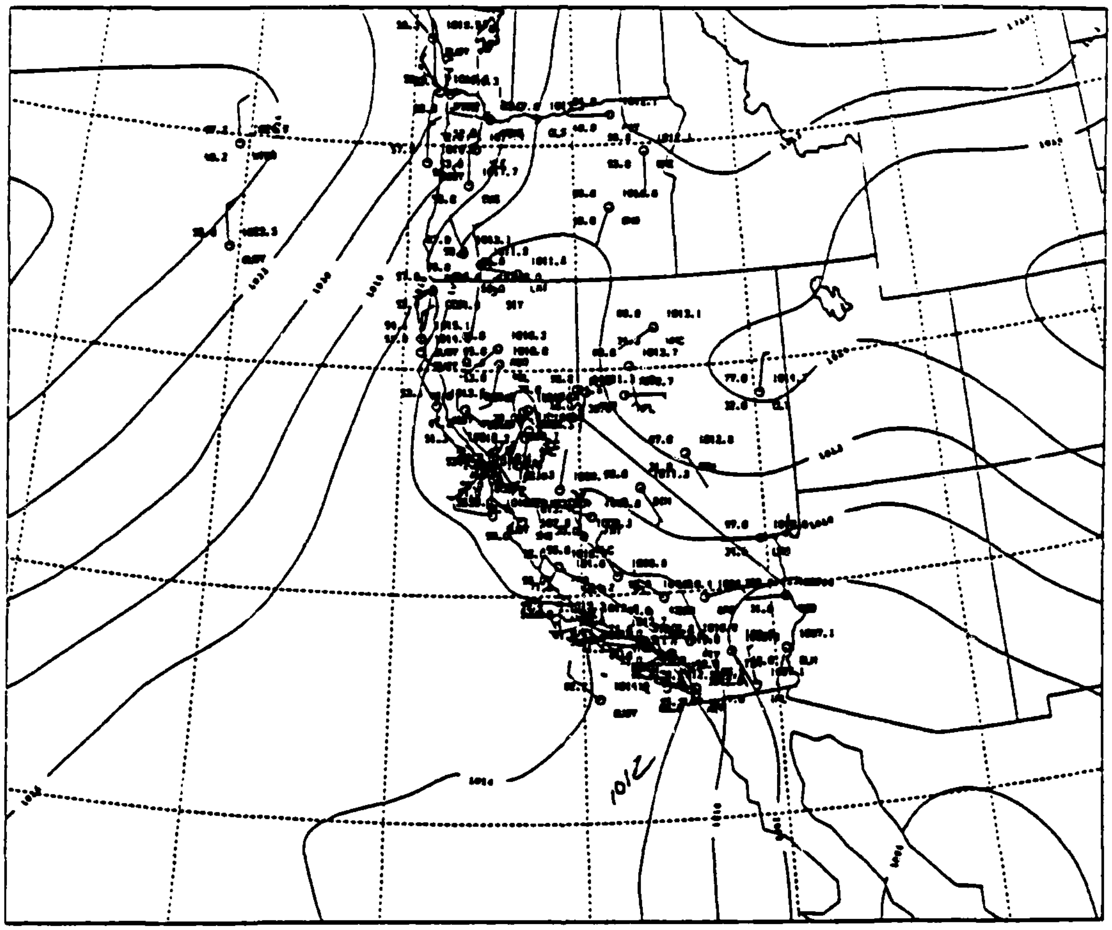


CONTOUR FROM 1006 TO 1026 BY 2

Figure 34. Surface pressure analysis for June 19 1993 at 21Z.

(4.0 mb) than case #3 (3.0 mb), yet did not yield stronger winds (13 kts and 15 kts respectively). The dominant factor separating these two cases (both trough regimes) appears to be the **strength** of the low-level temperature **inversion.** It is stronger for case #6 thus decoupling the vertical winds resulting in weaker surface ambient winds because of the reduction of downward **transfer** of high **momentum.**

C. GRADIENT REGIME

Similar to the Trough regime, the ambient wind variation in this Gradient regime is characterized by diurnal wind speed changes with little directional change as shown by case #8 depicted in Fig 35. Again similar to the Trough regime, wind conditions were calm until sea-breeze onset, then light westerly winds prevailed. By late afternoon (21Z) when the strong surface inversion had presumably dissipated, the wind speed reached 18 kts.

Case 8 (July 02/06Z - 03/06Z) typifies the influence of the Gradient regime on the temporal fluctuation of the intensity of the surface ambient wind. During the first period (06Z-18Z) the wind was initially northwest 0-05 kts becoming more southwesterly 05-08 kts by 12Z apparently under the influence of a passing weak low pressure trough, extending east-west across the Monterey Bay area (Fig 36). The second period (18Z-03Z) exhibited surface winds predominantly westerly 05-18 kts increasing steadily until 21Z, then

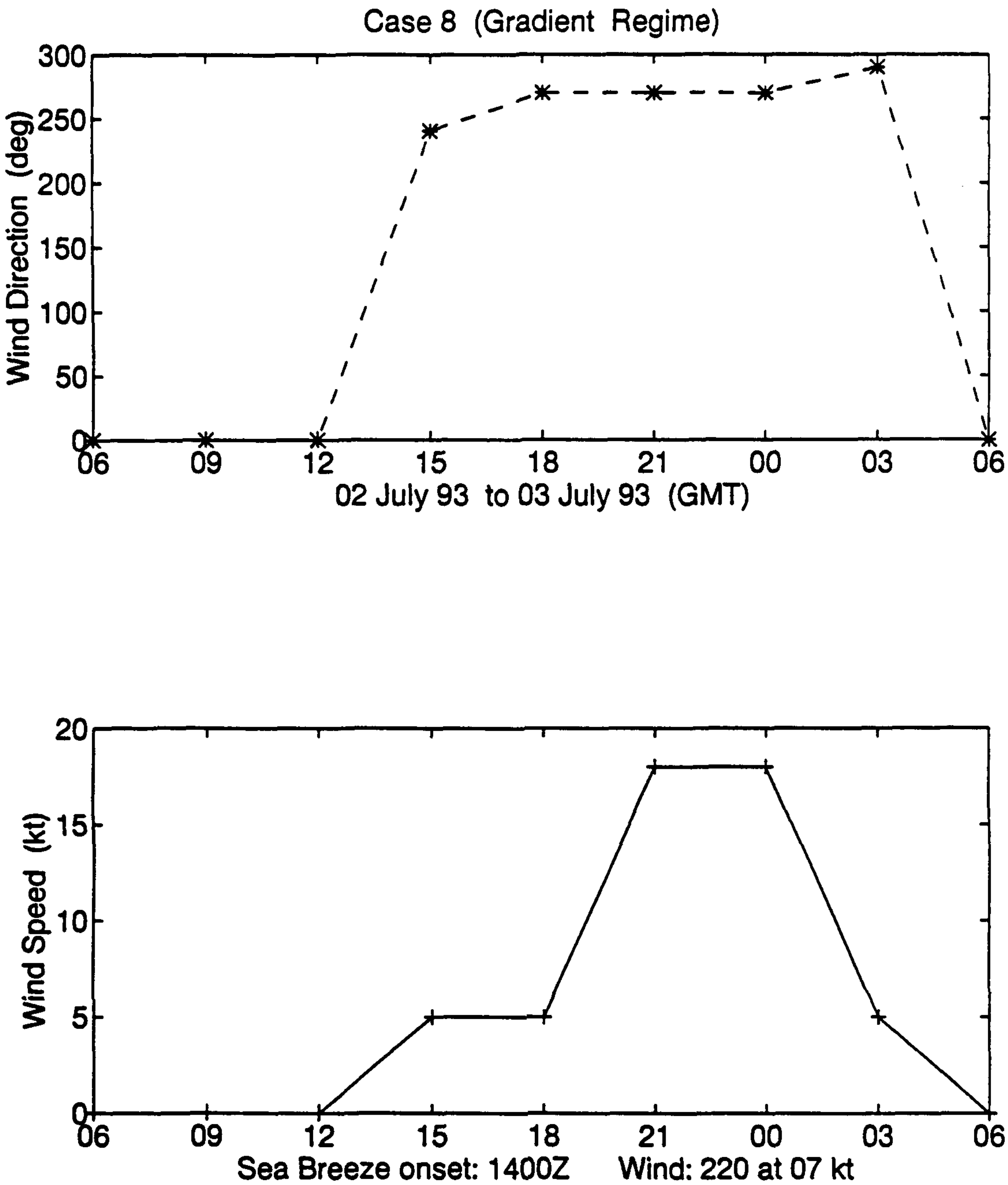
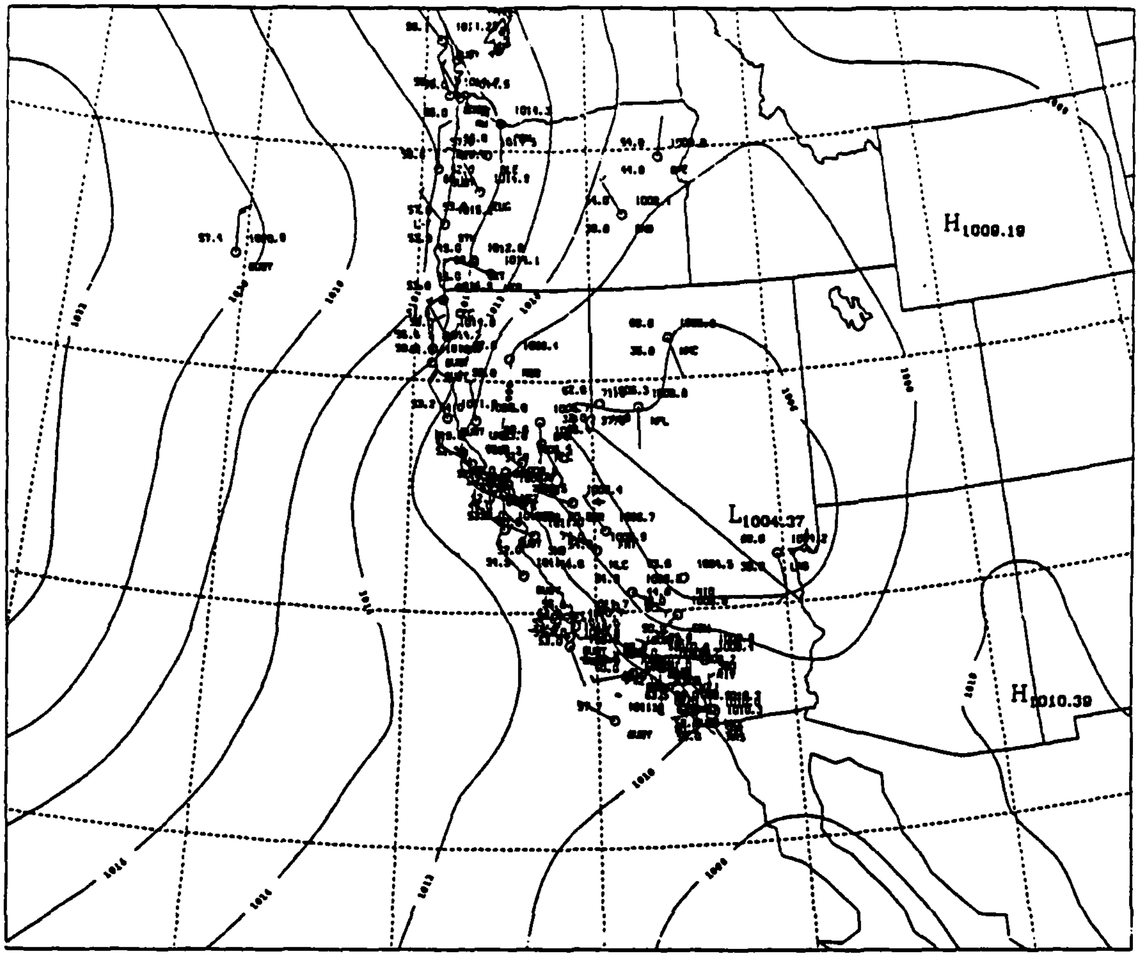


Figure 35. Case #8 wind speed - vs - direction comparison.

930702/1500 LL REGIØNAL ANALYSIS



CONTOUR FROM 1006 TO 1022 BY 2

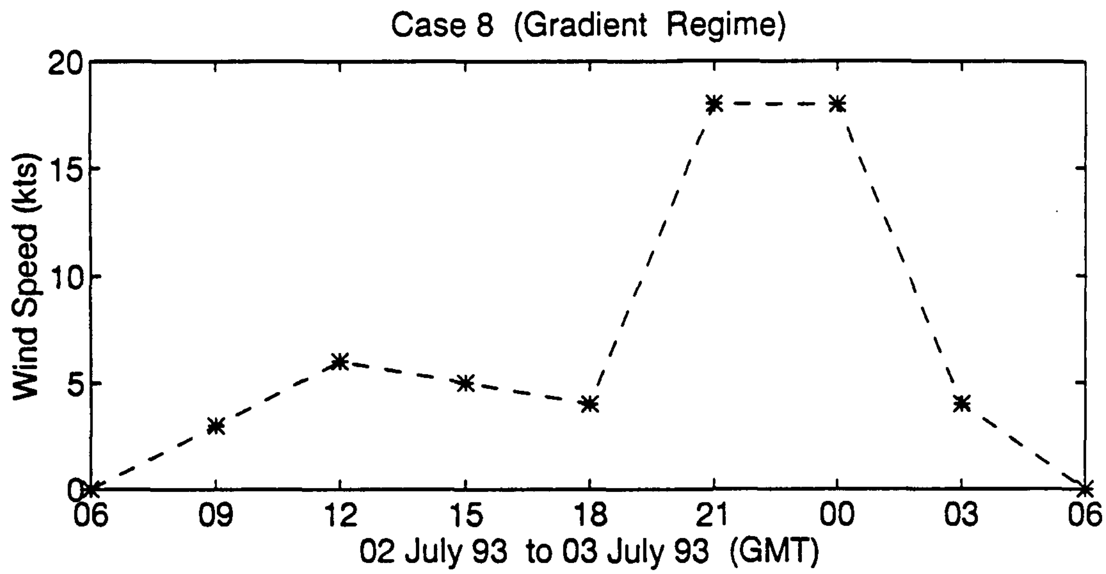
Figure 36. Surface pressure analysis for July 02 1993 at 15Z reflecting passage of weak surface low pressure trough.

decreasing steadily after 01Z. The third period (03Z-06Z) was predominantly west-northwest 0-05 kts steadily decreasing throughout the period (Fig 35).

This case study displayed the least correlation between the strength of the pressure gradient and the surface ambient wind intensity (Fig 37). There was a significantly closer correlation when the surface inversion completely dissipated by 03/00Z. The cross-coast pressure gradient varied between 6 and 8 mb over the 24 hour period with the largest difference occurring at 00Z. Despite the strong pressure gradient between 06Z & 18Z, the surface ambient wind did not increase until it dramatically increased between 18Z & 21Z. This wind increase was due to the increased surface heating which raised the marine boundary layer allowing for greater vertical mixing of the atmosphere. The strong pressure gradient of this Gradient regime case was ultimately associated with the **strongest** surface ambient winds of all 10 cases investigated (Table 6).

Time (Z)	P - Gradient (mb)	Wind Speed (kts)	Boundary Layer Height (mb)	Oakland Sounding
0600 - 1800	5.0 - 6.5	00 - 08	975	02/12Z
1800 - 0300	7.0 - 8.0	05 - 18	950	03/00Z
0300 - 0600	3.5 - 6.0	00 - 05	970	03/12Z

Table 6: Case #8: pressure gradient, wind speed & marine boundary layer height comparisons.



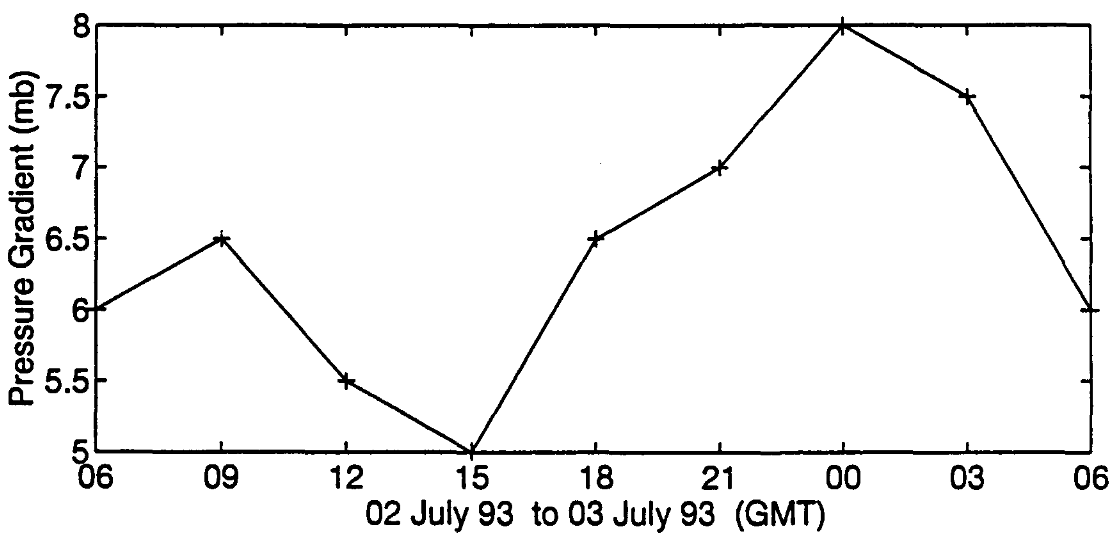


Figure 37. Case #8 wind speed - vs - pressure gradient comparison.

The boundary layer stability again appears to be the dominant influence on the diurnal fluctuation of the surface ambient wind. The 12Z sounding of the first period (06Z-18Z) shows a shallow boundary layer (975 mb) with a strong low-level temperature inversion (Fig 38) and a weak (0.5 deg C) surface inversion. The 00Z sounding of the second period (18Z-03Z), shows the boundary layer lifting to approximately 950 mb and the surface inversion dissipating (Fig 39) to produce a 6 deg C superadiabatic layer. This is characteristic of **strong** vertical **mixing** in this well mixed marine layer. Finally, the boundary layer in the third period (03Z-06Z) lowered to approximately 970 mb and the surface inversion (1.5 deg C) was reestablished by 12Z the next morning (Fig 40).

Case #8 began as a transitional regime between a Trough regime and a Gradient regime. The earlier periods of this case #8 were influenced similar to the Trough regime with the stability of the boundary layer playing a major role in the ambient wind speed fluctuations (Fig 41). It then took on the resemblance of a gradient regime by 02/15Z as the California thermal trough axis aligned itself further eastward over eastern California and western Nevada. The increased surface pressure gradient simultaneous with the **dissipation** of the surface **inversion** then became the dominant influence on the variability of the ambient wind intensity.

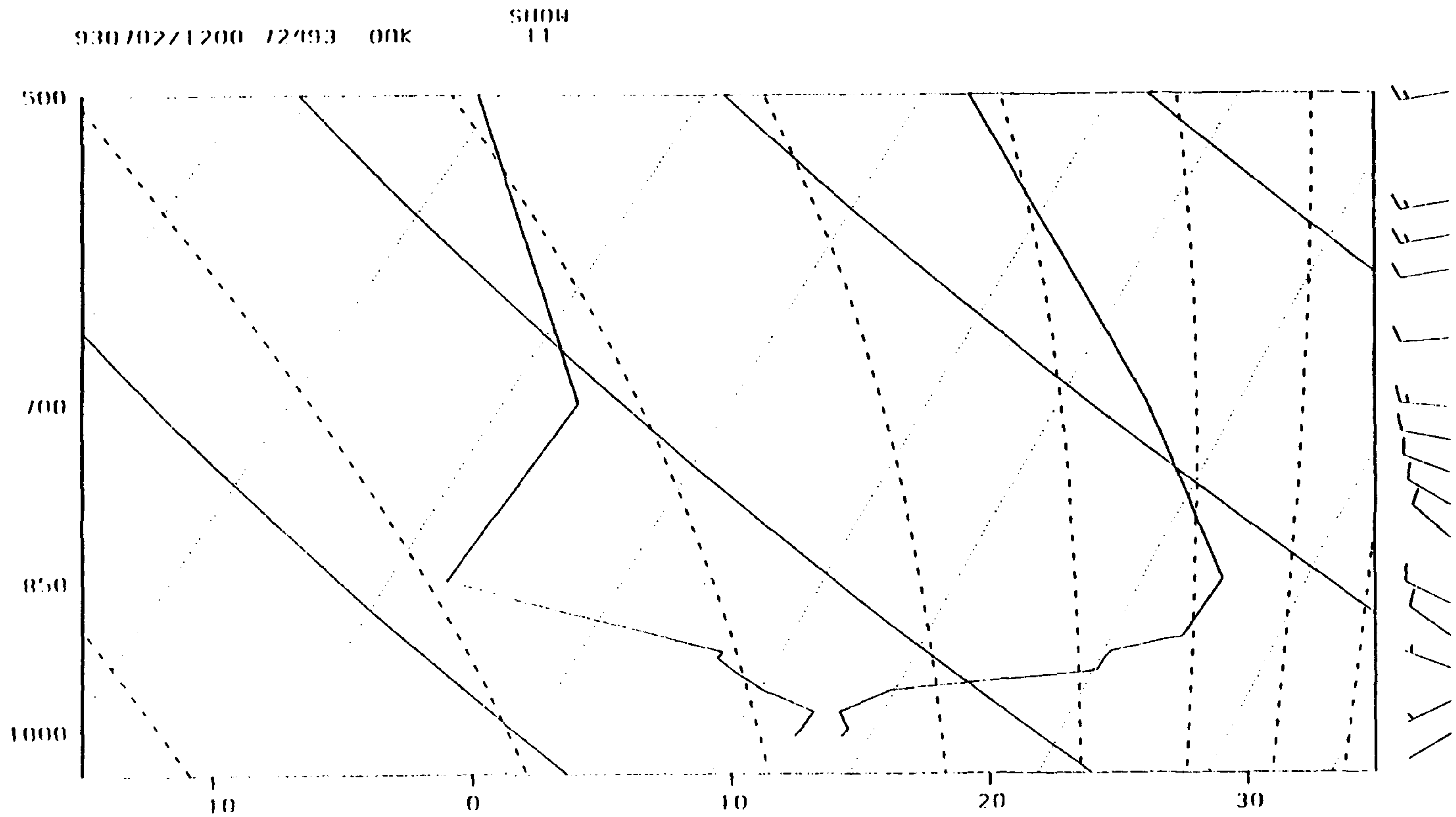


Figure 38. Oakland atmospheric sounding for July 02 1993 at 12Z.

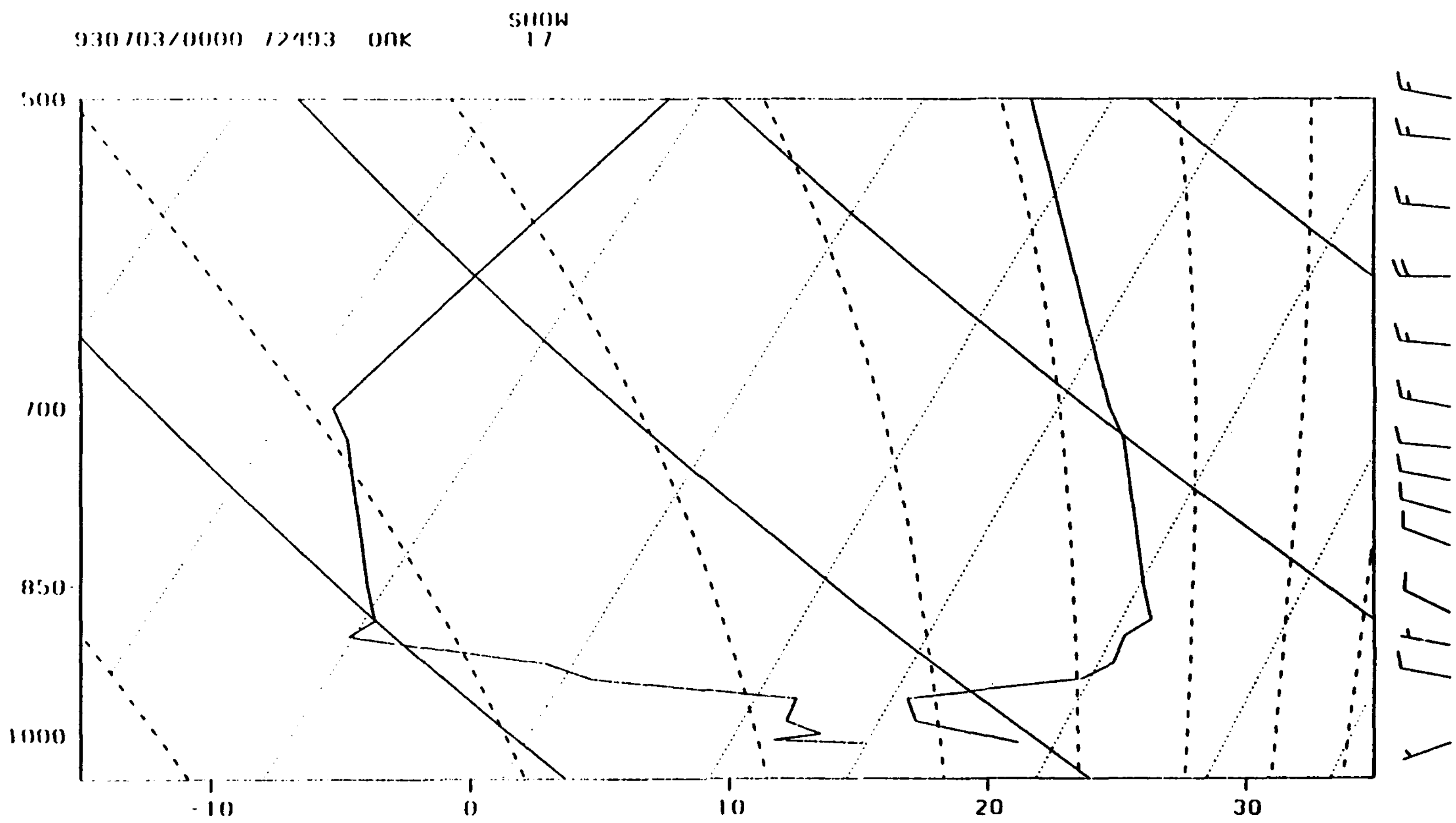


Figure 39. Oakland atmospheric sounding for July 03 1993 at 00Z.

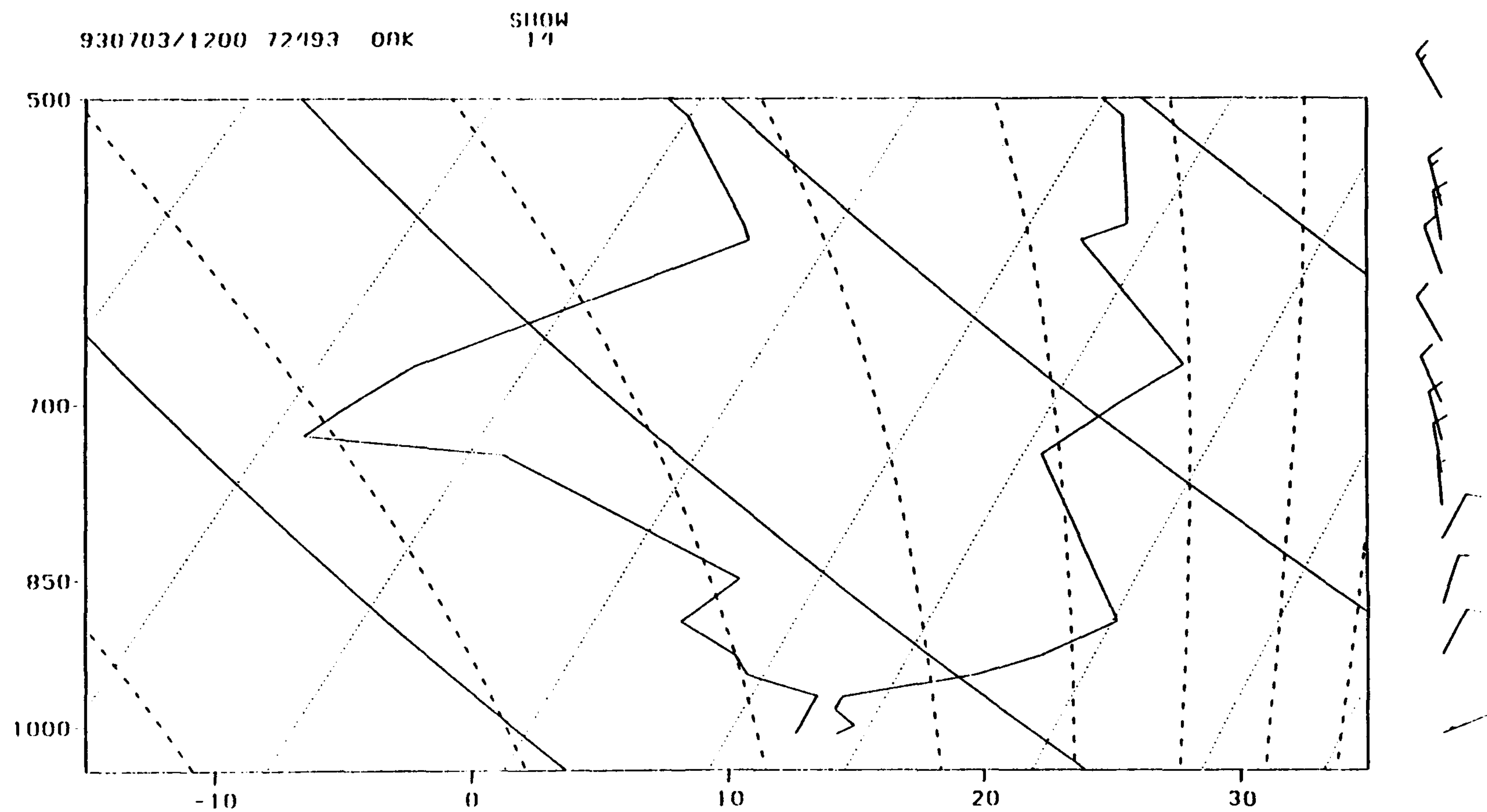


Figure 40. Oakland atmospheric sounding for July 03, 1993 at 12Z.

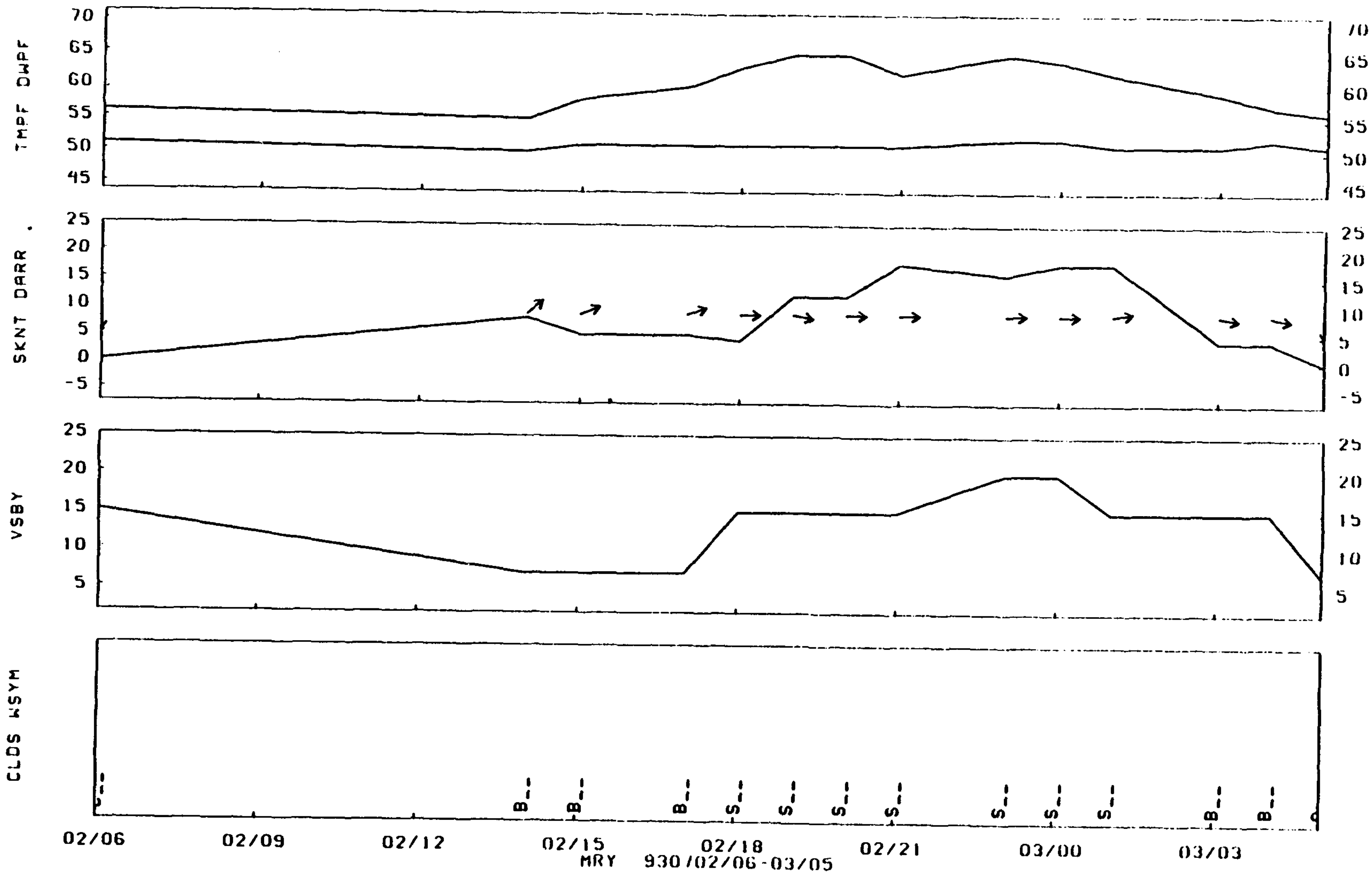


Figure 41. Time series of case #8 July 02/03Z-02/23Z 1993.

The stratus influence in this case appears to be a contributing factor in modifying the diurnal wind variation. Fig 41 shows that broken stratus persisted between 12Z and 18Z when the stratus became scattered. From 18Z to 01Z scattered low clouds prevailed while the ambient wind peaked at 21Z at 18 kts. The change from broken to scattered stratus coverage is associated with the surface heating and vertical mixing that occurs as the surface inversion dissipates. In this case, the **stratus** probably **slowed** the vertical **mixing** until the boundary layer dramatically changed at 18Z. At 03/03Z, while still probably under similar boundary layer characteristics as 00Z, the stratus increased in amount and the surface ambient winds immediately dropped off from 18 kts to 05 kts. This suggests that the clouds played a **significant** role in the sea-breeze intensity, which was hypothesized by Round (1993). However, the clouds appear to be more important in modifying the boundary layer **evolution** than enhancing the pressure gradient as suggested by Round (1993).

Comparing the analysis at the time of maximum wind speed of this strong sea-breeze day during case #8 (Fig 42) to the mean gradient pressure pattern over the region (Fig 4), it is clear that the 21Z 02 July pressure gradient is nearly twice that of the mean pressure gradient for this Gradient regime over the Monterey Bay. Fig 4 illustrates the mean pressure gradient having approximately a 2.7 mb gradient over Monterey Bay. Fig 42 depicts a 5.0 mb pressure gradient over the

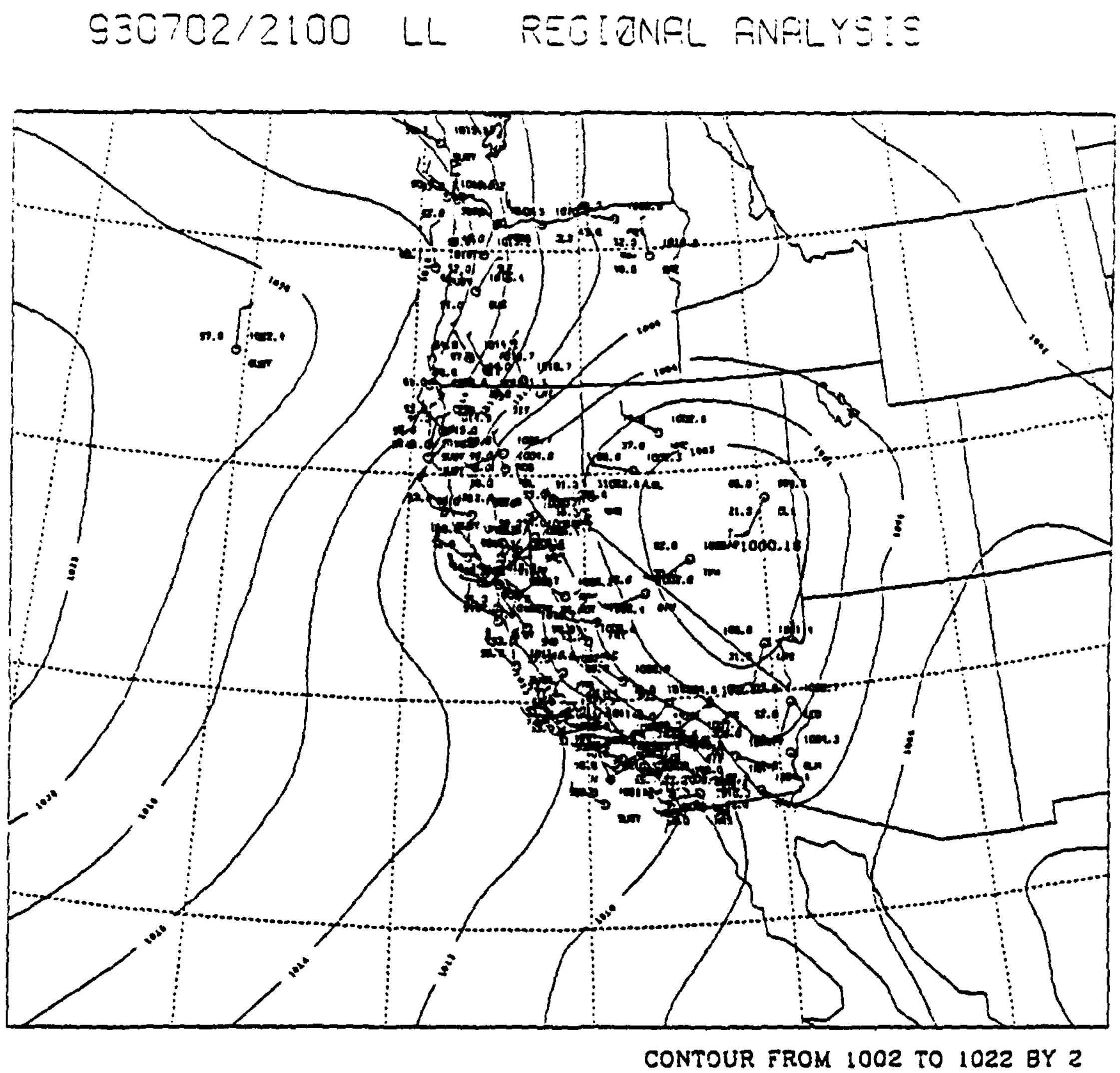


Figure 42. Surface pressure analysis for 02 July 1993 at 21Z.

region translating to the maximum wind of 18 kts for the 24 hour period.

Using Round's (1993) characterizations, this Gradient regime sea-breeze is also classified as a **clear onset type** sea-breeze consistent with the previous three case studies. Onset occurred at 14Z (0700 PST), shifting from calm conditions to 220 deg at 07 kts. The wind speed did not significantly increase until 19Z (1200 PST) when it increased to 12 kts.

D. REGIME INTERCOMPARISONS

Comparing the three regimes, it is evident that significant differences occur. The ambient wind variation of the Ridge regime was characterized by both diurnal wind speed and wind direction changes (case #1). The ambient wind variation of the Trough and Gradient regimes were characterized predominantly by diurnal wind speed changes with little directional change (cases #3, #6, & #8). The time of sea-breeze onset occurred consistently earlier for the Gradient regime (0700-0800 PST) than for the other two regimes (Table 4). The Trough regime had the time of onset consistently occurring at 1000 while sea-breeze onset for the Ridge regime occurred at 0900 or 1000 PST. This difference may be the result of the generally stronger pressure gradient in the Gradient regime. With the strong pressure gradient persisting through the night, stronger winds above the surface

inversion are likely. With minimal vertical mixing after sunrise the wind increases almost immediately.

The time of maximum wind speed of the sea-breeze for all regimes varied enough to prevent drawing any clear conclusions (Table 4). The intensity of the maximum wind was strongest for the Gradient regime occurring consistently between 15-18 kts. The intensity is again dependent on the strength of the low-level temperature inversion. The existence of the surface inversion directly corresponded to the relative intensity of the surface ambient winds for all three cases. The surface inversion decoupled the winds in the vertical keeping the surface ambient wind speed relatively weak. When the surface inversion significantly weakened or dissipated, the increased vertical atmospheric mixing led to increased surface wind speeds.

The Ridge regime exhibited a relatively close relationship between the change in wind speed and the corresponding cross-coastal sea-level pressure difference (Fig 16). Both the Trough and Gradient regimes showed little correlation until after the sea-breeze onset occurred (Figs 25 & 37). These correlation differences are evidently the result of the weak to non-existent surface inversion in the Ridge regime, which allows vertical mixing over the entire diurnal cycle and would allow the wind to respond to surface pressure gradient changes.

The stratus played a more significant role of influence in the Gradient regime than in the other two regimes. Stratus was absent in the Ridge regime (case #1). For the Trough regime (cases #3 & #6) the ambient wind was stronger for case #3 which had stratus and was weaker for case #6 which was cloud free. The weaker winds of the cloud-free case #6 are contrary to the expected influence of clouds on the surface heating, illuminating the prominent influence of the strength of the surface inversion. For the Gradient regime, stratus prevailed throughout but changed from broken to scattered at the time when the wind increased dramatically. This appears to be the result of a delay in boundary layer stability changes caused by the stratus damping the surface heating. Additionally, in the cases when the stratus increased in amount after the maximum wind was reached, the surface ambient wind speed immediately decreased, which also supports its impact on boundary layer stability.

The 18Z-03Z and 03Z-06Z time periods of case #1 (Ridge regime) and #6 (Trough regime) shared similar pressure gradients; however, the resultant surface ambient wind speed was significantly different (Tables 3 & 5 respectively). The major difference appears to be that case #1 had a deeper and more unstable boundary layer than case #6. This supports the observation of more continuous weak winds throughout the 24 hour period in case #1 with only modest afternoon wind speed enhancement. In case #6, the more stable boundary layer

seemed to prevent any surface wind signature until the afternoon heating allowed mixing and a substantial wind speed increase from 0 to 13 kts. The diurnal variability of the boundary layer depth between the two regimes was similar and produced somewhat similar surface ambient wind speeds. However, the Trough regime (case #3) again tended to show a more pronounced afternoon wind increase, which is consistent with a larger change in the surface layer stability between 12Z and 00Z.

The major difference between the Gradient and Trough regimes is that a greater surface pressure gradient occurs for the Gradient regime (3.5-8 mb) than for the Trough regime (1.0-4.2 mb). Surprisingly, the surface ambient wind speeds were similar for the two regimes (15 vs 18 kts) in spite of a nearly doubled pressure gradient. This difference is probably the result of the deeper marine layer in the Gradient regime and more persistent stratus. Considerably more heating is required to overcome the stratus and allow deep vertical mixing in the Gradient regime. The Gradient regime seems to represent a more persistent and mature synoptic situation where the boundary layer and pressure pattern had been established for a longer period of time than occurs in the Trough regime.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This study used hourly station reports, synoptic analyses and soundings to investigate the characteristics of the sea-breeze under various synoptic-scale pressure patterns that prevailed over the Monterey Bay area during the spring/summer of 1993. Three separate synoptic-scale pressure patterns were identified that dominated the domain of study, which have been referred to as the Ridge, Trough, and Gradient regimes. The **Trough** regime was the most common occurrence during the spring/summer of 1993, occurring in approximately 52% of the analyses investigated. This regime constituted 4 out of 10 selected case studies and had a consistent time of sea-breeze onset of 1000 PST with surface ambient winds of 11-15 kts (Table 7). Three of the four Trough regimes studied showed that a boundary layer **destabilization** due to afternoon heating correlated strongly with the surface wind speed **increases** in the afternoon. The other case had little or no surface inversion in the Oakland sounding but followed a similar diurnal cycle. The consistent sea-breeze onset time of the Trough regime indicates the dominant influence of the **differential heating** of the atmosphere requires a relatively **longer** time to modify the atmosphere sufficiently to excite

Case # / Regime	*Time of Sea Breeze Onset (PST)*	*Maximum Ambient Wind (kts)*	*Time of Maximum Wind (PST)*
1 / Ridge	0900	12	1400
2 / Ridge	1000	15	1800
3 / Trough	0800	15	1300
4 / Gradient	0700	12	1700
5 / Trough	1000	11	1500
6 / Trough	1000	13	1700
7 / Gradient	0800	15	1700
8 / Gradient	0700	18	1400
9 / Gradient	1000	15	1300
10 / Trough	1000	12	1400

Table 7. Regime comparisons.

the momentum **mixing** than it does for the Ridge and Gradient regimes.

The **Gradient** regime was the second most prevalent of the three regimes. It occurred in approximately 27% of the analyses investigated. This regime generated the strongest sea-breeze winds and had the largest cross-coast pressure difference (case #8 - Table 6). This indicates that the **synoptic-scale** pressure pattern prevailing at the time of occurrence had a **stronger** influence on the resultant wind speed intensity than the differential heating of the coastal region. The surface heating was responsible for destabilizing the boundary layer, mixing down the stronger winds aloft to

the surface. This regime displayed a consistently earlier time of sea-breeze onset (0700-0800 PST) than the other two regimes (Table 7) indicating the atmosphere needed less time to produce sufficient momentum mixing to generate relatively strong surface winds.

The **Ridge** regime was the regime of least occurrence, occurring in 13% of the analyses investigated and predominantly during the month of May. With only two of the ten cases investigated fitting this category, conclusions are less definitive. It appears that weaker boundary layer stability allowed the winds to respond to the diurnal variation in the pressure gradient produced by differential heating. This seemed to delay the time of sea-breeze onset until 0900 or 1000 pst (Table 7).

A miscellaneous category, those analyses that clearly did not fit in either a trough, ridge, or gradient regime, accounted for the remaining 8% of the analyses investigated. This category was inconclusive and consequently was not investigated.

Of the ten selected strong sea-breeze days investigated, **60%** can be associated with Round's (1993) characterization of a **clear onset type** of sea-breeze as defined in Chapter four. Cases #2 & #9 can be categorized as a frontal type sea-breeze as the onset resembled frontal characteristics with a definite wind shift and significant wind speed increase at sea-breeze onset. Cases #4 & #7 can be best categorized as the gradual

type sea-breeze displaying a gradual shift to sea-breeze conditions (Table 2).

The **coupling** of the winds above and below the boundary layer after dissipation of the 12Z surface inversion produce a **strong** diurnal wind speed **enhancement** during all regimes. Stratus differs in its amount of influence between all three regimes. The amount of stratus appears to be a stronger influence during the Gradient regime and plays less of a role of influence during the Ridge and Trough regimes.

In conclusion, this study suggests that the primary factor influencing the diurnal wind cycle in the Monterey Bay area is the boundary layer **depth** and **stability**. A strong cross-coast pressure gradient persists most of the time over the 24 hour cycle which would support relatively strong boundary layer winds throughout the day. The diurnal heating cycle simply causes this momentum to be mixed down to the surface in the afternoon increasing the surface wind speeds. It then de-couples during the evening and nighttime hours resulting in decreased surface wind speeds. **Clouds** can significantly slow the **destabilization** of the boundary layer particularly during the Gradient regime, which tends to have a deeper boundary layer and more stratus.

B. RECOMMENDATIONS

These results should be extended by more carefully examining the relative roles of the boundary layer momentum

mixing and thermally driven cross-coast pressure gradients for the Monterey Bay. Soundings for the Monterey Bay are required as is higher temporal resolution in the vertical structure to better understand the influence of the California coastal jet, and all other influences on the surface wind speeds over the Monterey Bay area. A more complete analysis of the relationship between the synoptic regime and the boundary layer structure and clouds should also be addressed.

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